PRICE TEN SHILLINGS AND SIXPENCE

THE JOURNAL OF
The Institution of Electrical Engineers

FEB [illegible]
GUINDY

ORIGINALLY
The Society of Telegraph Engineers
FOUNDED 1871
INCORPORATED BY ROYAL CHARTER 1921
EDITED BY P. F. ROWELL, SECRETARY
SAVOY PLACE, VICTORIA EMBANKMENT, LONDON, W.C.2
Telegrams: "VOLTAMPERE, PHONE, LONDON." Telephone: TEMPLE BAR 7676.

Vol. 80 JUNE, 1937 No. 486

CONTENTS.

(The Institution is not, as a body, responsible for the opinions expressed by individual authors or speakers.)

PAGE
Apparatus used for High-Power Switchgear Testing .... J. S. CLIFF 593
Discussion on "The Properties of a Dielectric containing Semi-Conducting Particles of Various Shapes" 609
Control of Wireless Signal Variations ... A. L. GREEN, M.Sc., Ph.D., and G. BUILDER, Ph.D. 610
Control of Phase-Fading in Long-Distance Radio Communication. A. L. GREEN, M.Sc., Ph.D., and O. O. PULLEY, B.E., Ph.D. 623
Optimum Symmetrical Light Distributions .... H. R. S. MCWHIRTER, B.Sc.(Eng.) 636
Discussion on "A Review of Recent Developments in Rural Electrification" 643
Nickel-Iron Alloys of High Permeability, with special reference to Mumetal. W. F. RANDALL, B.Sc. 647
Discussion on "The Electrical Characteristics of 132-kV Line Insulators under Various Weather Conditions" 667
Discussion on "The High-Pressure Mercury-Vapour Lamp in Public Lighting" 669
Discussion on "Equipment and Performance of Steel-Tank Rectifier Traction Substations operating on the Underground Railways of the London Passenger Transport Board" 672
Proceedings of The Institution 676
Institution Notes 677
Advertisements .... At end i–xviii

E. and F. N. SPON LIMITED, 57 HAYMARKET, LONDON, S.W.1.
CHEMICAL PUBLISHING COMPANY OF N.Y. INC., 148 LAFAYETTE STREET, NEW YORK.

The Institution of Electrical Engineers.

FOUNDED 1871

INCORPORATED BY ROYAL CHARTER 1921

PATRON: HIS MAJESTY KING GEORGE VI.

COUNCIL, 1936–1937.

President.

H. T. YOUNG.

Past-Presidents.

COLONEL R. E. CROMPTON, C.B., F.R.S.
SIR JAMES SWINBURNE, BART, F.R.S.
W. M. MORDEY.
SIR JOHN SNELL, G.B.E.
CHARLES P. SPARKS, C.B.E.
ROGER T. SMITH.
LL. B. ATKINSON
J. S. HIGHFIELD.
F. GILL, O.B.E.
A. RUSSELL, M.A., D.Sc., LL.D., F.R.S.
W. B. WOODHOUSE.
W. H. ECCLES, D.Sc., F.R.S.
SIR ARCHIBALD PAGE.
LIEUT.-COL. K. EDGCUMBE, T.D.
COLONEL SIR THOMAS F. PURVES, O.B.E.
CLIFFORD C. PATERSON, O.B.E.
J. M. DONALDSON, M.C.
PROF. E. W. MARCHANT, D.Sc.
P. V. HUNTER, C.B.E.
PROF. W. M. THORNTON, O.B.E., D.Sc., D.Eng.
J. M. KENNEDY, O.B.E

Vice-Presidents.

A. P. M. FLEMING, C.B.E., M.Sc.
W. E. HIGHFIELD.
SIR GEORGE LEE, O.B.E., M.C.
JOHNSTONE WRIGHT.

Honorary Treasurer.

F. W. CRAWTER.

Ordinary Members of Council.

A. H. M. ARNOLD, Ph.D., D.Eng.
SIR NOEL ASHBRIDGE, B.Sc. (Eng.).
J. R. BEARD, M.Sc.
E. S. BYNG.
T. CARTER.
C. E. FAIRBURN, M.A.
F. FORREST.
PROF. C. L. FORTESCUE, O.B.E., M.A.
P. GOOD.
E. M. LEE, B.Sc.
BRIG.-GENERAL R. F. LEGGE, C.B.E., D.S.O.

Ordinary Members of Council—(*Continued*).

S. W. MELSOM.
F. E. J. OCKENDEN.
P. J. ROBINSON, M.Eng.
J. W. THOMAS, LL.B., B.Sc.Tech.
V. WATLINGTON, M.B.E.
C. R. WESTLAKE.
W. J. H. WOOD.

Chairmen and Past-Chairmen of Local Centres.

Argentine Centre:
H C. SIDDELEY.
*R. WRIGHT.

China Centre:
C. R. WEBB.
*C. S. TAYLOR.

Irish Centre:
W. STOREY.
*R. G. ALLEN.

Mersey and North Wales (Liverpool) Centre:
F. E. SPENCER.
*O. C. WAYGOOD.

North-Eastern Centre:
D. M. BUIST.
*F. C. WINFIELD, M.Eng.

North Midland Centre:
S. R. SIVIOUR.
*COL. H. C. FRASER, D.S.O., O.B.E., T.D.

North-Western Centre:
G. L. PORTER.
*E. C. McKINNON.

Scottish Centre:
H. C. BABB.
*J. B. MAVOR.

South Midland Centre.
E. A. REYNOLDS, M.A.
*F. H. CLOUGH, C.B.E.

Western Centre:
J. W. SPARK.
*H. M. ROBERTS.

* Past-Chairman.

Chairmen of Sections.

G. F. SHOTTER (*Meter and Instrument*).
P. DUNSHEATH, O.B.E., M.A., D.Sc. (*Transmission*).
E. MALLETT, D.Sc.(Eng.) (*Wireless*).

Secretary.

P. F. ROWELL.

Assistant Secretaries.

F. W. HEWITT, M.Sc.; A. E. RAYNER.

LOCAL CENTRES AND SUB-CENTRES.

ARGENTINE CENTRE.

Chairman.—H. C. SIDDELEY.

Hon. Secretary.—R. G. PARROTT, Avenida Pte. Roque Saenz Peña 636, Buenos Aires.

CHINA CENTRE.

Chairman.—C. R. WEBB.

Hon. Secretary.—J. HAYNES WILSON, M.C., c/o Shanghai Telephone Co., P.O. Box 1193, Shanghai, via Siberia.

IRISH CENTRE.

Chairman.—W. STOREY.

Hon. Secretary.—R. N. EATON, 1, Foster Place, College Green, Dublin.

MERSEY AND NORTH WALES (LIVERPOOL) CENTRE.

Chairman.—F. E. SPENCER.

Hon. Secretary.—W. PARRY, M.Eng., "Scaur," Birkenhead Road, Gt. Meols, Hoylake, Wirral, Cheshire.

NORTH-EASTERN CENTRE.

Chairman.—D. M. BUIST.

Hon. Secretary.—H. B. POYNDER, "Eastnor," Jesmond Park, Newcastle-on-Tyne, 6.

Tees-Side Sub-Centre.

Chairman.—W. S. RAMSDALE.

Hon. Secretary.—H. SHAW, "Glenholme," Boosbeck, Saltburn, Yorks.

NORTH MIDLAND CENTRE.

Chairman.—S. R. SIVIOUR.

Hon. Secretary.—W. R. T. SKINNER, B.Sc.(Eng.), 36, Park Place, Leeds, 1.

Sheffield Sub-Centre.

Chairman.—A. R. CHAYTOR.

Hon. Secretary.—A. C. BOSTEL, Tapton Cliffe, Fulwood Road, Sheffield, 10.

[*Continued on page (III) of Cover*

APPARATUS USED FOR HIGH-POWER SWITCHGEAR TESTING

By J. S. CLIFF, Associate Member.

(*Paper first received* 23*rd June*, 1936, *and in final form* 12*th February*, 1937; *read before the* NORTH MIDLAND CENTRE, *at Leeds*, 19*th January*, 1937.)

SUMMARY

The paper deals with the equipment and construction of a modern high-power testing laboratory capable of testing circuit breakers of ratings up to 1 500 MVA at voltages up to 132 kV.

General details of the power circuit are given, including the generator, super-excitation system, load and power factor control, step-up and step-down transformers, and switchgear.

The metering and instrument equipment is also described, particulars being given of both low- and high-frequency oscillographs and their associated components.

TABLE OF CONTENTS

Introduction.

General Layout of Plant.

Part I. Power Circuit.

Generator. Generator driving motor. Generator field circuit. Master circuit-breaker. Reactors. Resistors. Making switch. High-voltage transformers. Low-voltage transformer. Test bays. Oil supplies.

Part II. Metering and Instrument Equipment.

Low-frequency oscillograph. Shunts. Current transformers. Potential transformers. Potential dividers. Fluid-pressure recorder. Cross-bar travel recorders. Pilots. Cathode-ray oscillographs. Short-circuit timing.

Other apparatus.

Acknowledgements.

Introduction

Within the last few years the importance of avoiding electrical power shutdowns due to switchgear failure during short-circuits has increased considerably. Supply engineers require definite guarantees from the makers that their circuit breakers are capable of reliably rupturing their rated breaking capacity, and that associated apparatus will withstand the stresses imposed during short-circuits. These points can only be proved by direct tests at full power.

In the absence of an independent testing station, several of the larger switchgear manufacturers have built their own test plants. This paper briefly outlines the major features in the design and construction of one of these stations.

General Layout of Plant

The object of the plant is to reproduce controlled short-circuits having characteristics as similar as possible to the faults liable to occur on supply networks. When the station was planned in 1933, consideration of the design of the generator showed that a single machine would be sufficient for testing circuit breakers rated up to 1 500 MVA (1 MVA = 1 000 kVA). As this covered the majority of the switchgear then contemplated for manufacture it was decided to build the laboratory round a single generator, space being left on the site for duplicating the generating plant should future requirements demand it.

The general layout of the station finally adopted is shown in Fig. 1, the more important electrical circuits being shown diagrammatically in Fig. 2. The distance between the generator and the test bays has been kept as short as possible, the main conductors being run in a direct line out of the generator, through the master circuit-breaker, over the top of the reactors and resistances, through the making switch, and straight into the larger test bay. The busbars are of 3 in. diameter copper tube, very heavily braced to a steel supporting framework from which they are insulated by bakelized paper cylinders and wooden clamps. The capacitance to earth has been kept as low as possible to ensure a high natural frequency of electrical oscillation for the circuit. Reactors and resistances are put into circuit by opening links in the main busbar run.

The high-voltage transformers are located at the side of the smaller test bay, while the low-voltage transformer is mounted close to one side of the larger test bay in order to keep the heavy-current connections as short as possible. The leads to the primaries of these transformers are connected to the main busbars on the side of the maker switch remote from the generator, so that this switch can be used for closing short-circuits at all voltages.

Before each series of tests the generator room is vacated and the plant controlled solely from the observation room. This practice has been adopted in the interests of the safety of the operating staff in the event of a breakdown on the test plant, and also to obviate the necessity of screening all live high-voltage connections.

The observation room is situated on a bank overlooking the test bays, which are about 30 yards distant. The main room is divided into two sections, the one containing the low-frequency oscillograph, the pendulum timing control, the firing board, and the generator control board, the other being used as a general office. Behind the main room is situated the dark room, entered through a light trap, and provided with lightproof hatches for passing the camera drums in and out. At the rear of the dark room is the cathode-ray oscillograph room, also provided with a hatch for the rapid transference of films. Below the observation room is built a long

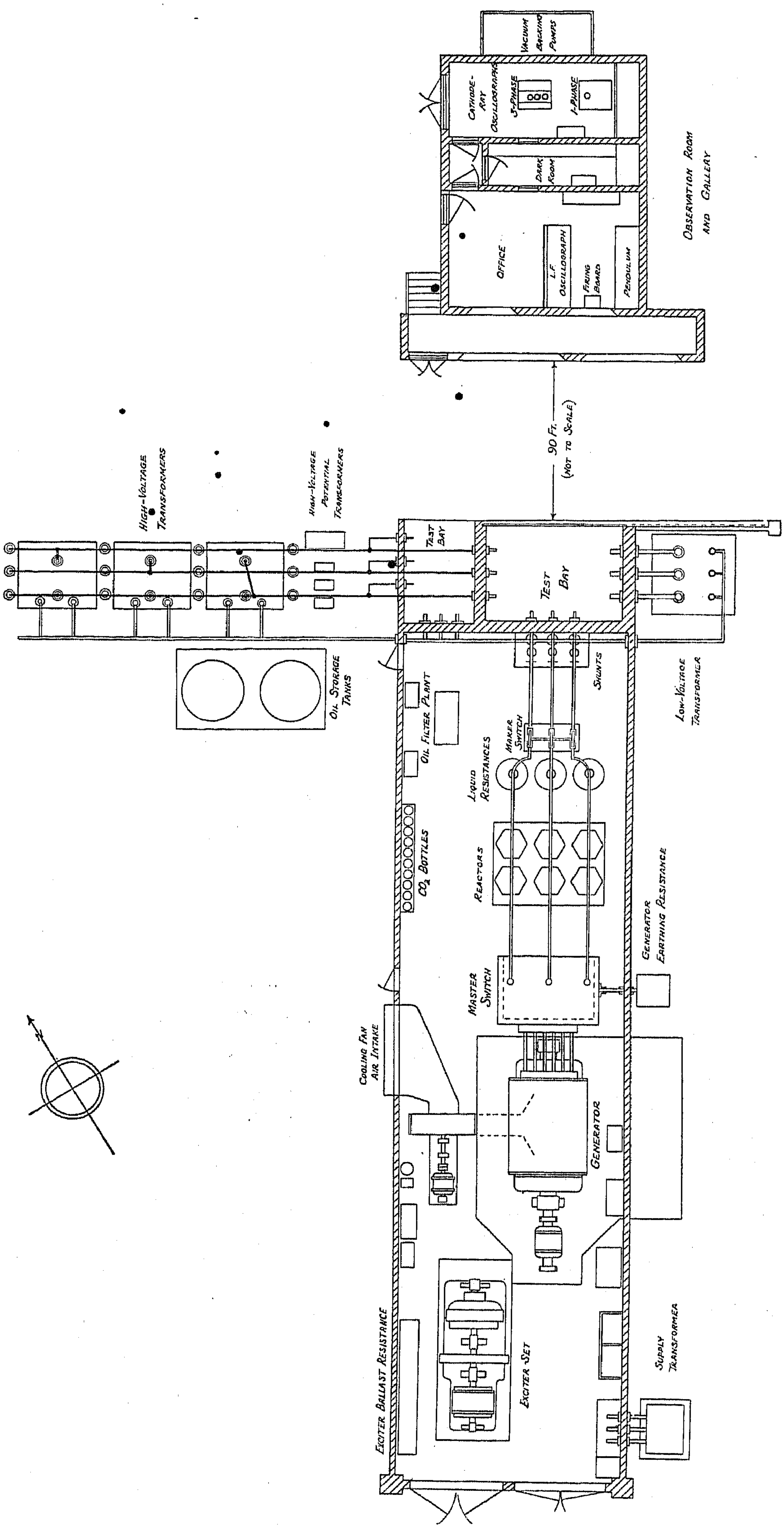


Fig. 1.—General layout.

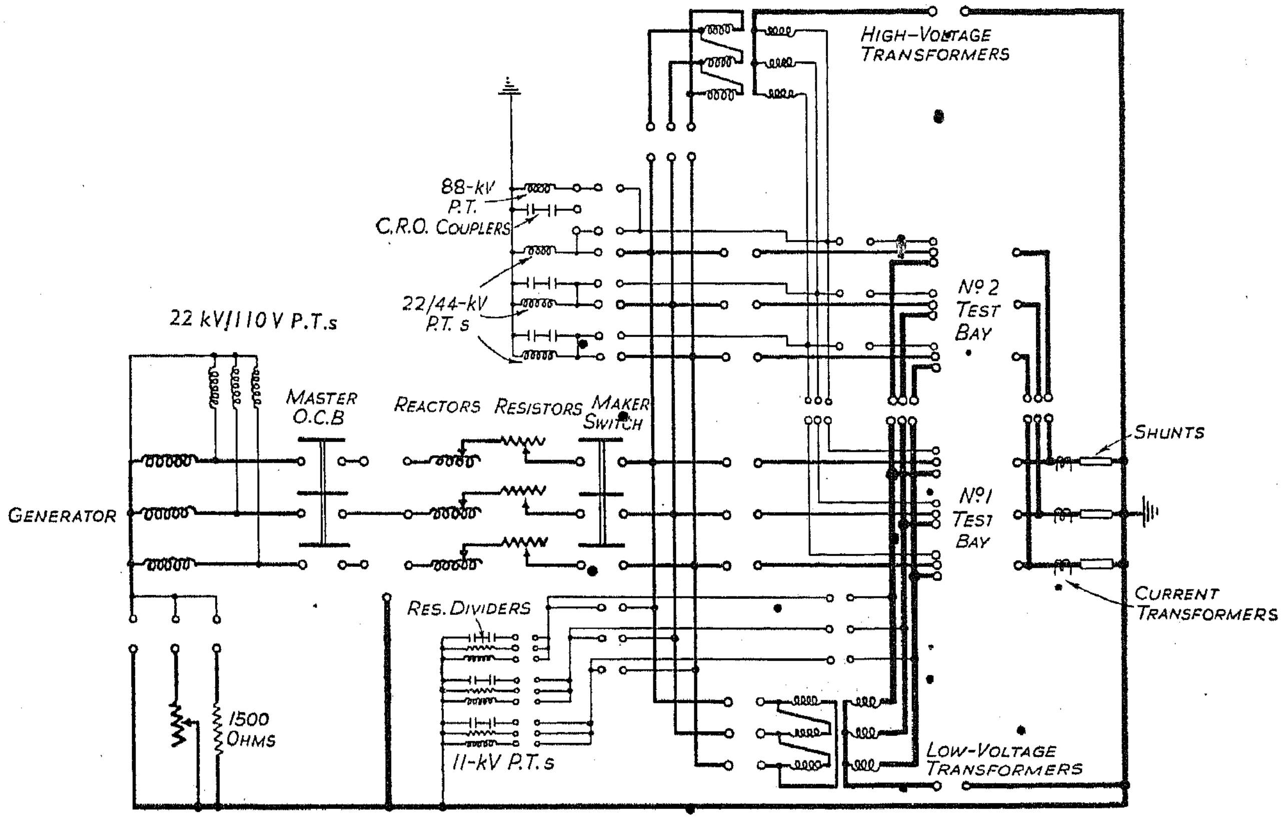


Fig. 2.—Main circuit connections.

gallery provided with viewing windows and capable of holding 50 persons.

In close proximity to the test bays is a workshop where circuit breakers are prepared for test and have minor modifications and overhauls made to them. The test area is enclosed to prevent unauthorized persons from entering during testing.

PART I

POWER CIRCUIT

Generator

Since for an equivalent frame size a 2-pole alternator can be made with larger output than a low-speed machine, the generator was designed for 3 000-r.p.m. operation. The frame size is approximately the same as that of a standard 50 000-kVA machine, the stator weighing 80 tons and the rotor 23 tons.

The short-circuit power output of a generator varies approximately as the square of its voltage, and maximum output can therefore only be obtained for full field current. It follows that to obtain full short-circuit capacity at several testing voltages the stator connections must be changeable to give alternative voltages for full field current. Each phase has accordingly been wound in two sections, arranged for series/parallel connection, and the three phases can be coupled either star or delta. The nominal voltages at normal full field are: series/star, 22 kV; series/delta, 12·7 kV; parallel/star 11 kV; parallel/delta, 6·35 kV. There is sufficient overvoltage margin for the parallel/delta connection to be used for testing 6·6-kV apparatus. Intermediate voltages are obtained by field regulation. When the phases are connected in star the neutral point can, if desired, be earthed either solidly or through a variable liquid resistance.

The decrement of the symmetrical component of the short-circuit current is of the greatest importance, since, when testing circuit breakers in accordance with specifications such as the revised B.S.S. No. 116—1929, which insists upon the opening of the circuit being delayed until the d.c. component of the short-circuit current has fallen below 20 per cent, the ruptured-current value may be greatly reduced if the decrement is large. As the recovery voltage is also reduced proportionately, the loss in testing power may be considerable, thus lowering the effective testing capacity of the plant.

Since the a.c. decrement is caused by the demagnetization of the field by the flux due to the stator current it is possible to reduce it by increasing the field excitation during the short-circuit, and thus counteracting the armature reaction. This is done by employing an extra-large exciter capable of supplying the normal generator field through a series resistance which can be cut out during the test, thus increasing the field current to several times its normal value. The circuit used for this is shown in Fig. 3. Before the short-circuit the field is adjusted to the required value with the contactor open and the ballast resistance in circuit. A few cycles before the short-circuit is applied the contactor is closed, cutting out the resistance and boosting the field current. At the conclusion of the test the excitation is removed by opening the field circuit of the main exciter.

The ballast resistance used has a maximum value of 1·0 ohm. The maximum voltage of the main exciter is 1 200 volts, and when this is applied to the rotor the current is boosted from the normal full value of 900 amperes to 4 500 amperes. The amount of boost selected depends upon the MVA value of the short-circuit applied, and is varied by adjusting the value of the ballast resistance. The resistance is made in four sections of 0·25 ohm, each capable of carrying 900 amperes for 15 minutes, and arranged for series/parallel connections, enabling 10 resistance values to be obtained.

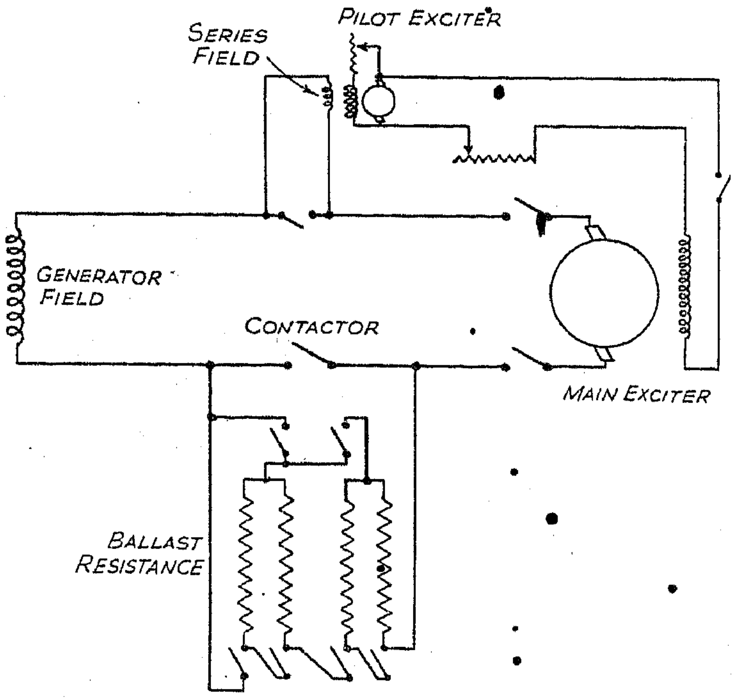


Fig. 3.—Generator field boosting circuit.

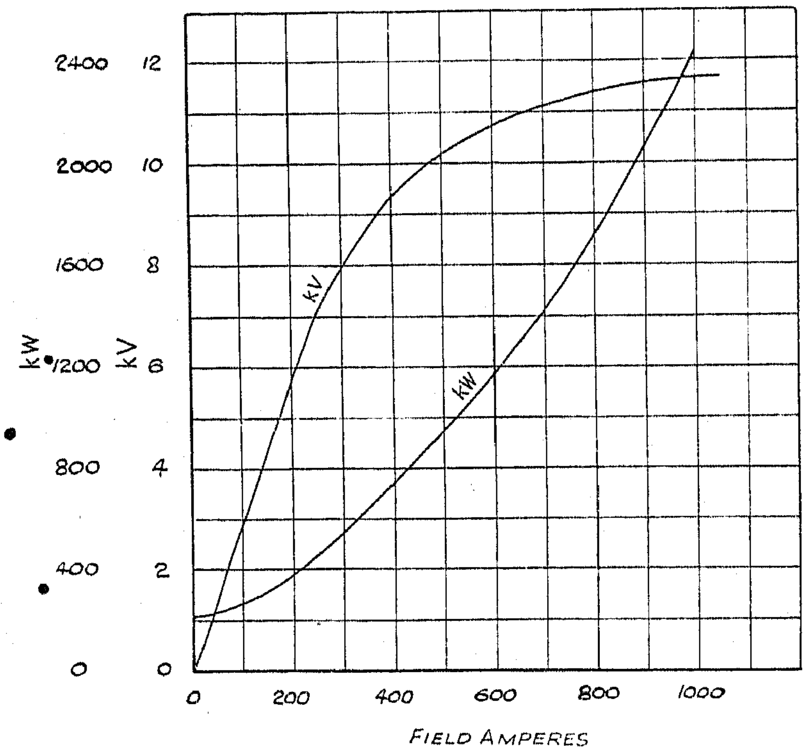


Fig. 4.—Normal open-circuit characteristic.

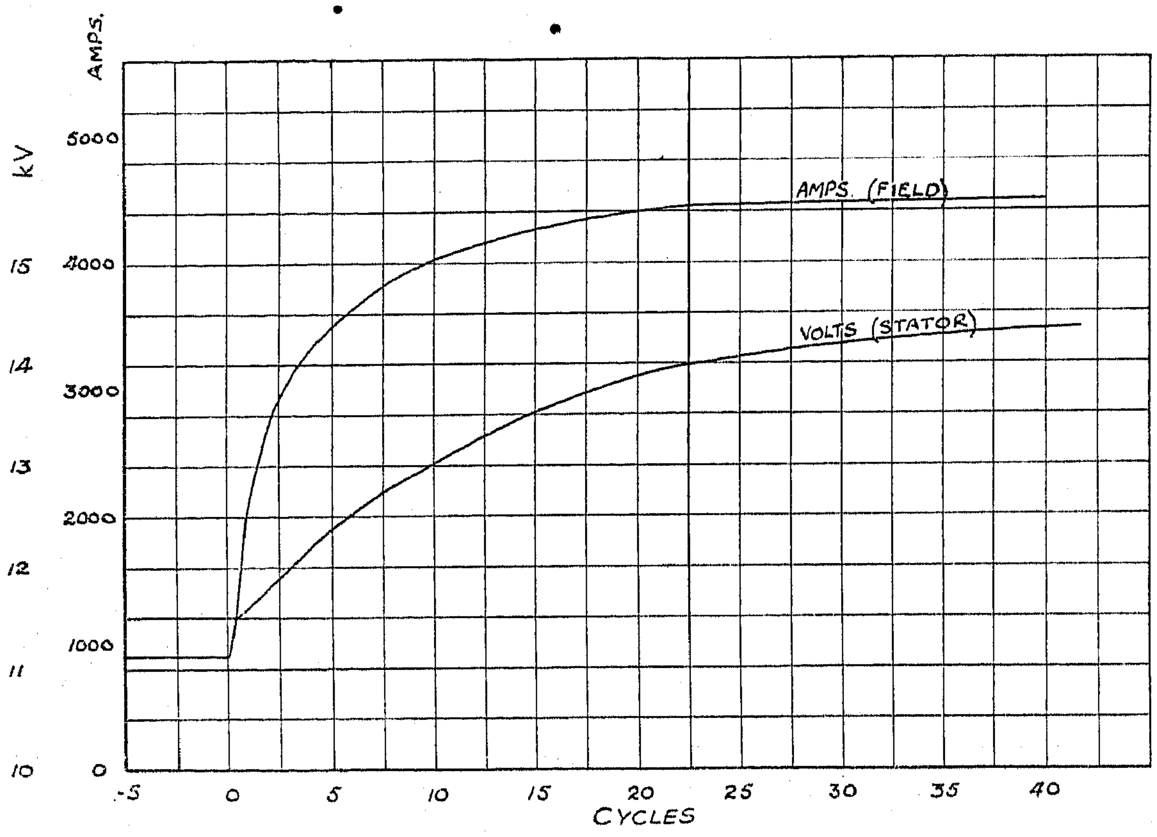


Fig. 5.—Boosted open-circuit characteristic.

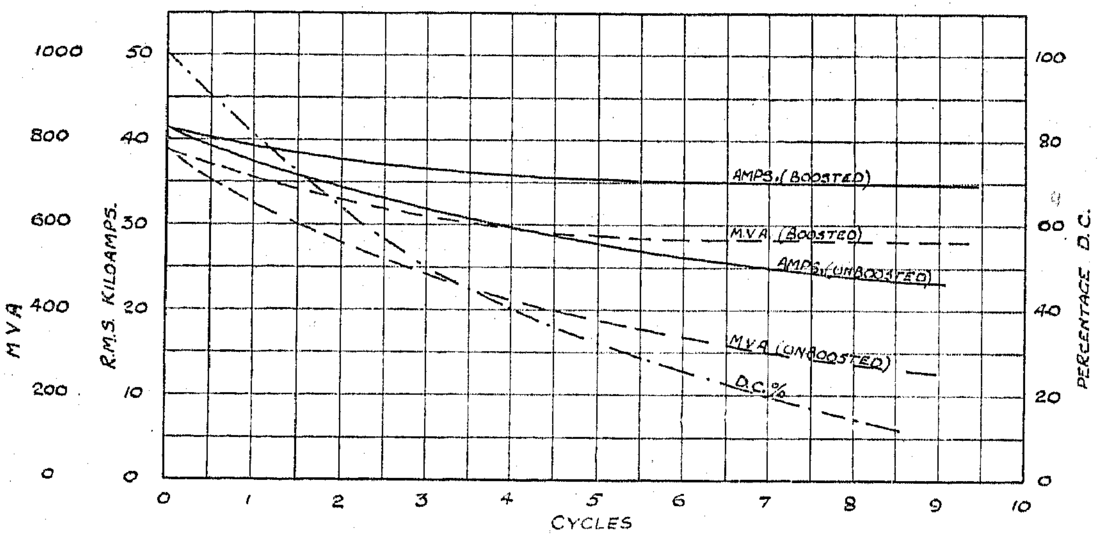


Fig. 6.—Effect of using super-excitation.

When super-excitation is used on a testing generator it must be designed to operate with the field well saturated at the working voltage. This avoids large voltage-rises due to the abnormal exciting current, and helps to stabilize the flux and so reduce the demagnetization. Fig. 4 is the open-circuit characteristic of the generator when connected in parallel/star, and is taken up to the normal full field current of 900 amperes. The figure also indicates how the driving-motor input increases as the field is applied.

The continuation of the open-circuit characteristic for boosted values of field current above 900 amperes is given in Fig. 5, this being derived from an oscillogram taken by adjusting the field to 900 amperes and then cutting out the 1·0-ohm ballast resistance, the excitation and stator voltage increasing as shown.

The curves in Fig. 6 illustrate the advantage of super-excitation. Without field boosting the short-circuit current falls to 25 kiloamperes from its initial value of 41 kiloamperes by the time the d.c. component has fallen to 20 per cent, the MVA (based on symmetrical current multiplied by recovery voltage) falling to 300 from 780 MVA. With exactly the same circuit constants but employing super-excitation during the short-circuit, the corresponding figures are 35 kiloamperes and 570 MVA, this being nearly double the unboosted power output. The above figures are taken from tests at approximately half the output of the generator. For tests at lower MVA values the a.c. decrement is still further reduced by using field boosting, and can be completely annulled for short-circuits below 500 MVA.

With the stator connected in parallel/star the reactance of the generator (including busbars to the test bay and shunts) is 0·07 ohm per phase at normal full field, the stator voltage being 11·8 kV. The initial symmetrical short-circuit current per phase is therefore:—

$$\frac{11\cdot 8}{0\cdot 07 \times 1\cdot 73} = 97 \text{ r.m.s. kiloamperes}$$

Hence the normal instantaneous output during the first half-cycle, calculated on open-circuit voltage and symmetrical current, is $97 \times 11\cdot 8 \times 1\cdot 73 = 2\,000$ MVA.

If the asymmetrical value of current (resultant of a.c. and d.c. components) is used, this value is increased to 2 800 MVA. By applying the maximum super-excitation approximately 25 cycles before the short-circuit the stator voltage can be increased to 14 kV, as shown in Fig. 5. The initial symmetrical short-circuit current per phase is then increased to 116 r.m.s. kiloamperes, this giving an instantaneous symmetrical output during the first half-cycle of 2 800 MVA, the asymmetrical value of this being nearly 4 000 MVA.

The stator frame is of fabricated steel and is in direct contact with the concrete foundations. The concrete raft on which the machine stands is 32 ft. long by 28 ft. wide by 12 ft. deep, is heavily reinforced with steel, and weighs 450 tons. The subsoil is almost pure rock sand. The stator winding end-turns are very heavily braced to prevent movement, the major forces being restrained by 2-in. diameter manganese-steel studs screwed into a manganese-bronze casting attached to the end of the stator frame. A further bronze casting fitted over the ends of the steel studs braces them radially, and also forms a damping winding. The 12 leads from the stator windings are brought out of the top of the frame in order to facilitate running connections from them and also to obviate pits in the foundations.

The rotor is made from a solid forging of high-grade carbon steel and follows standard turbo-alternator practice except that the insulation is increased for the 1 200-volt super-excitation, and the slots are shallower than is usual in order to maintain strength in the steel. A special damping winding is inserted in the rotor slots above the field winding to assist in the reduction of the short-circuit current decrement. The slip-rings and brushgear are liberally designed to carry the abnormal exciting current.

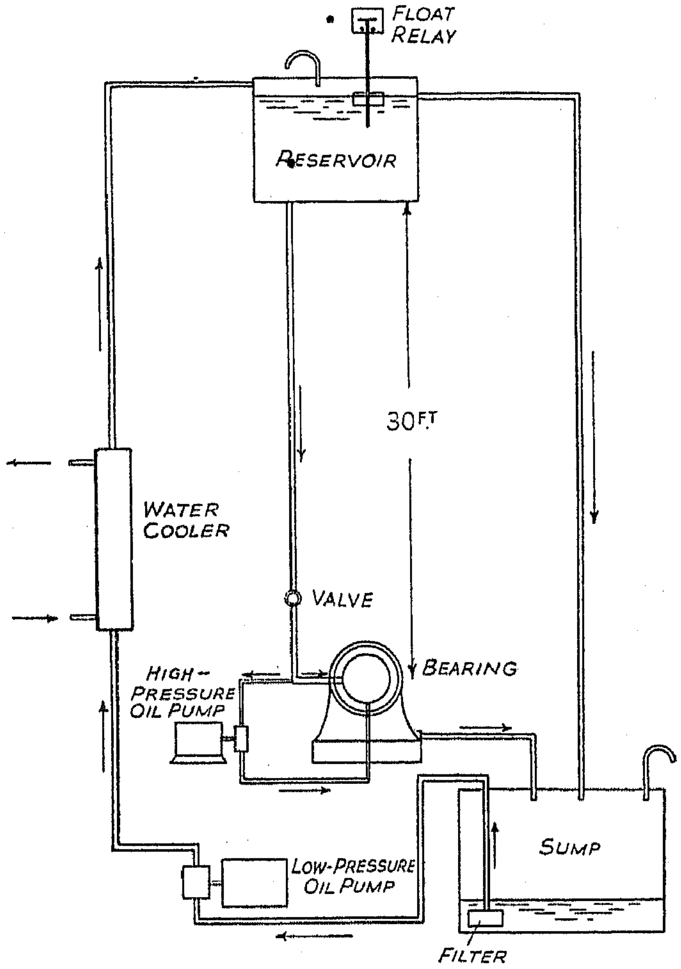


Fig. 7.—Generator oiling system.

Forced-draught cooling is supplied by an external fan, driven by a 130-h.p. motor, delivering 50 000 cu. ft. of air per minute. The air is drawn in from outside the laboratory through an oil filter having an area of 136 sq. ft. and after passing through the machine discharges into the room from the top of the stator. Doors are provided in both the fan intake and the stator outlet. These are tripped automatically should the electrical protective relays operate, indicating an insulation failure in the stator winding. At the same time eight 50-lb. cylinders of carbon-dioxide gas are automatically released into the stator to minimize any fire hazard.

The rotor bearings follow standard practice, but are amply designed since they are subject to shocks during short-circuits. Thermocouples and contact thermometers are fitted to give warning of overheating. High-pressure pumps injecting oil at 1 000 lb. per sq. in. under the bearings are provided to assist starting and relieve the duty on the driving motor.

The oiling system has received very careful consideration since, owing to the high inertia of the rotor, it takes about 40 minutes to come to rest from full speed, and oil must be supplied during this period should all auxiliary power fail.

The arrangement adopted is shown diagrammatically in Fig. 7. The top reservoir holds 900 gallons of oil and is always maintained full by the low-pressure pump which delivers slightly more than the bearings pass at full speed (35 gallons per minute), the surplus returning to the sump through the overflow pipe, which is large enough to pass the full output of the pump when the generator is at rest. Should the level in the top reservoir fall, indicating that the pump has stopped, the float relay switches off the driving motor and warns the attendant.

The oil is cooled by an air cooler situated in the generator main fan intake, this being supplemented by a water cooler during hot weather.

The windings of the generator are protected by standard McColl relays set to operate for a fault current of 100 amperes and overload relays set at 500 amperes. The latter operate through a definite time-delay relay adjustable from 0 to 10 sec.

Generator Driving Motor

The driving motor is quite small in size compared with the generator, since it is only used to run the rotor up to full speed and supply the open-circuit losses. Just before each test the motor is disconnected from the mains, the kinetic energy stored in the generator rotor being used to supply the short-circuit losses. Referring to Fig. 4, it will be seen that approximately 200 kW are required to drive the rotor unexcited, and 2 050 kW at the full normal field of 900 amperes. As the full excitation is only applied for short periods the motor has been designed to give 2 500 h.p. for 10 minutes, with 30 minutes between duties. The motor is of the slip-ring induction type, the stator voltage being 550 volts, and it is cooled by air tapped from the generator fan circuit. A flexible coupling is used between the two machines. The motor can be used for emergency braking of the generator by reversing two of the stator leads. In this manner the rotor can be brought to rest in about 5 minutes.

The starter is of the liquid type, the electrodes being motor-operated. The design is such that the maximum resistance is sufficient for braking and the minimum low enough to be short-circuited by a contactor without an excessive current surge. The closing of the contactor returns the starter automatically to the full resistance position, where it is ready for bringing the rotor back up to speed again for the next test or emergency braking if required. The duty on the starter is very onerous since it is used after each test, and the drop in rotor speed during the short-circuit is considerably increased by the use of super-excitation. The electrolyte is circulated through a large radiator, and as many as 30 restarts have been made in a day without overheating.

Generator Field Circuit

The main exciter runs at 480 r.p.m. and follows standard d.c. generator design. It will give 1 200 volts at 900 amperes, this increasing to 4 500 amperes plus the reflection of the short-circuit during the test. It is also used for testing d.c. circuit breakers, the ballast resistance then being used as a load-limiting resistance, and will give peaks of 15 000 amperes without flashover. The driving motor is of the slip-ring induction type, and this also is switched off prior to the short-circuit test, the energy required during the test being supplied by a 13-ton flywheel. The ballast resistance must necessarily be large in size since it has to dissipate nearly the full output of the exciter before the test. It consists of cast-iron grids arranged in a bank and cooled by a fan.

Master Circuit-breaker

The generator is protected by a master circuit-breaker which clears the circuit should the apparatus under test fail, or consist of a reactor or transformer. An oil circuit-breaker fitted with explosion pots is used and is capable of rupturing the full output of the generator if necessary. The contacts are those of a standard 3 000-ampere breaker. The circuit breaker is closed by compressed air at 100 lb. per sq. in., obtained from a compressor plant which is also connected with the test bays for the operation of pneumatically-closed circuit breakers under test.

Table 1

MINIMUM SHORT-CIRCUIT MVA AVAILABLE USING REACTORS AND TRANSFORMERS

Test voltage	Short-circuit current	MVA	Transformer ratio
kV	amperes		kV
0·22	3-phase, 900	0·35	11/1·9
0·44	3-phase, 450	0·35	11/3·8
0·66	3-phase, 700	0·80	11/3·8
2·2	3-phase, 100	0·38	11/19
3·3	3-phase, 50	0·30	11/33
6·6	3-phase, 25	0·30	11/66
11	3-phase, 42	0·80	11/66
22	3-phase, 84	3·20	11/66
33	3-phase, 130	7·50	11/66
44	3-phase, 160	12·50	11/66
66	3-phase, 260	30	11/66
114	1-phase, 127	14·50	11/114

Reactors

In order to vary the short-circuit current output of the generator and still maintain a low power factor to comply with switchgear specifications, inductance must be introduced into the circuit. This takes the form of concrete reactors of similar type to those used in power stations but filled in solid with concrete to increase their mechanical strength. Four reactors are employed per phase, the maximum reactance being 4·2 ohms. To obtain very low values of MVA the transformers are used in conjunction with the reactors, the generator voltage being reduced correspondingly. The minimum values of MVA available are given in Table 1. A range of lower values of reactance down to 0·028 ohm in 53 steps is obtained by tappings and series/parallel connections of the reactors made by latched knife switches. For single-phase tests the reactors in all three phases can be connected in parallel to obtain further values of inductance.

Resistors

To carry out tests at higher power factors, and when it is necessary to accelerate the decrement of the d.c. component of the short-circuit current, resistance must be added to the circuit. This is obtained by specially-designed liquid resistances. The dimensions of the tanks are given in Fig. 8. Using water from the local well the resistances have a value of slightly over 1·0 ohm when full; by lowering the water level a maximum working resistance of 4·5 ohms per phase can be obtained. Values below 1·0 ohm are achieved by adding concentrated washing-soda solution, mixed quickly by agitating the electrolyte with compressed air. The ohmic values are measured by the volt/ampere method using low-voltage alternating current from a metering panel permanently mounted beside the resistances.

Making Switch

A separate switch is employed for closing the short-circuit for " break " tests. Since it never has to break any power its construction is relatively simple. The contacts are air-insulated to facilitate inspection and maintenance, and are arranged in sets on quickly-removable copper castings, 16 pairs of contact fingers being used on each fixed terminal. The moving contacts consist of two vee-shaped blades in parallel per phase, each pair being removed by slackening a single clamping bolt. The average life of a set of contacts is about 6 months. To prevent excessive burning when making currents of the order of 300 kiloamperes (peak) the closing speed has been made high, the travel of the moving blades being kept small. A total break of 4 in. (two breaks in series) per phase has been found quite sufficient for 22-kV service. The moving contacts are latched open against two powerful compression springs, the latch being tripped by a small solenoid to close. The switch is opened and the springs re-compressed by the direct pull of a solenoid. The current is led into the switch in such a direction that the electromagnetic forces acting upon the cross-bar do so in the same direction as the closing springs, and thus tend to hold the contacts more firmly together.

High-voltage Transformers

For tests above 22 kV, step-up transformers are used. Three similar single-phase units have been installed, the primaries arranged for operation at either 11 or 22 kV each, the secondaries at 19 or 38 kV each. The primaries are connected in delta for 3-phase working, or in parallel for single-phase tests. The secondary voltages obtainable are:—

Three-phase. Parallel/delta, 19 kV; parallel/star, 33 kV; series/delta, 38 kV; series/star, 66 kV. The neutral point may be either earthed or insulated.

Single-phase. Parallel/parallel, 19 kV; series/parallel, 38 kV; parallel/series, 57 kV; series/series (2 transformers), 76 kV; series/series (3 transformers), 114 kV. The reactance of the transformer bank is slightly less than that of the generator, so that the 3-phase output is approximately half of that obtainable using the generator alone. Where the circuit breaker has a greater rupturing capacity than this, single-phase tests are made.

Each transformer is of modified shell construction, which enables strong circular coils to be used and also permits the close interleaving of the high-voltage and low-voltage coil groups necessary to obtain the low reactance figure required. Each complete coil stack is clamped between fabricated chrome-steel headers which are compressed by four 3-in. bolts of 65-ton steel. Extensions fitted to the bolts pass through oiltight glands in the transformer tank top, so that the coil clamping can be tightened easily without opening the casing. The transformers are oil-immersed in rectangular tanks, no cooling tubes or radiators being necessary in view of the short duration of the current flow. Each phase weighs 40 tons.

To safeguard the transformer windings against voltage surges which may occur during testing, surge arresters are installed on both primary and secondary lines, and also at the neutral point when it is insulated. The secondary-side arresters are so arranged that their discharge voltage can be varied to suit the transformer connections employed.

Table 2

Kilovolts	R.M.S. kiloamps.	Connections	
3·8	30	Series	Star
2·2	52	Series	Delta
1·9	60	Series/parallel	Star
1·1	104	Series/parallel	Delta
0·95	120	Parallel	Star
0·55	208	Parallel	Delta

Low-voltage Transformer

To enable tests to be made on low-voltage switchgear a stepdown transformer has been installed. As the maximum rupturing capacity required at the lower voltages is considerably less than at higher voltages the size of this transformer has been reduced, provision being made for testing up to 150 MVA. The three phases are accommodated in one tank, oil-immersed and self-cooled. The primary is connected for 11-kV working voltage. Each secondary phase is wound in four similar sections capable of being connected in series/parallel, the three phases being coupled either in star or in delta. The secondary voltages and currents are as shown in Table 2. Intermediate voltages are obtained by generator-field manipulation. Although the very heavy currents obtainable on the lower voltages are not required for rupturing tests, they are very useful for carrying out heavy-current heating and electromagnetic-stress tests on bus-bar structures, etc. To keep the connections short for these tremendous currents, the transformer has been mounted immediately against the larger test bay (see Fig. 1). Since owing to the low potential it is possible to cut off heavy-current arcs before the current passes through a normal zero, the transformer may produce

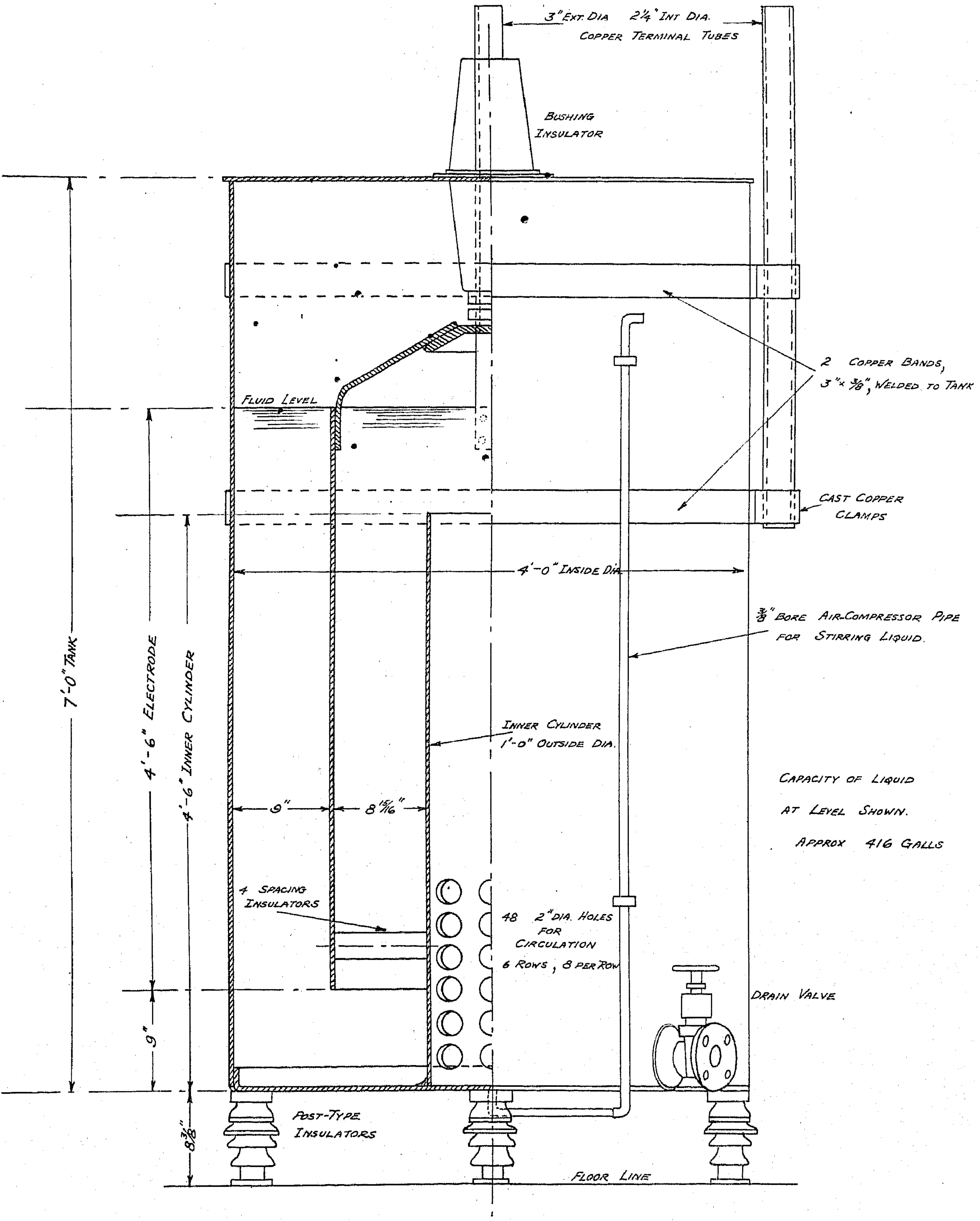


Fig. 8.—Liquid resistance.

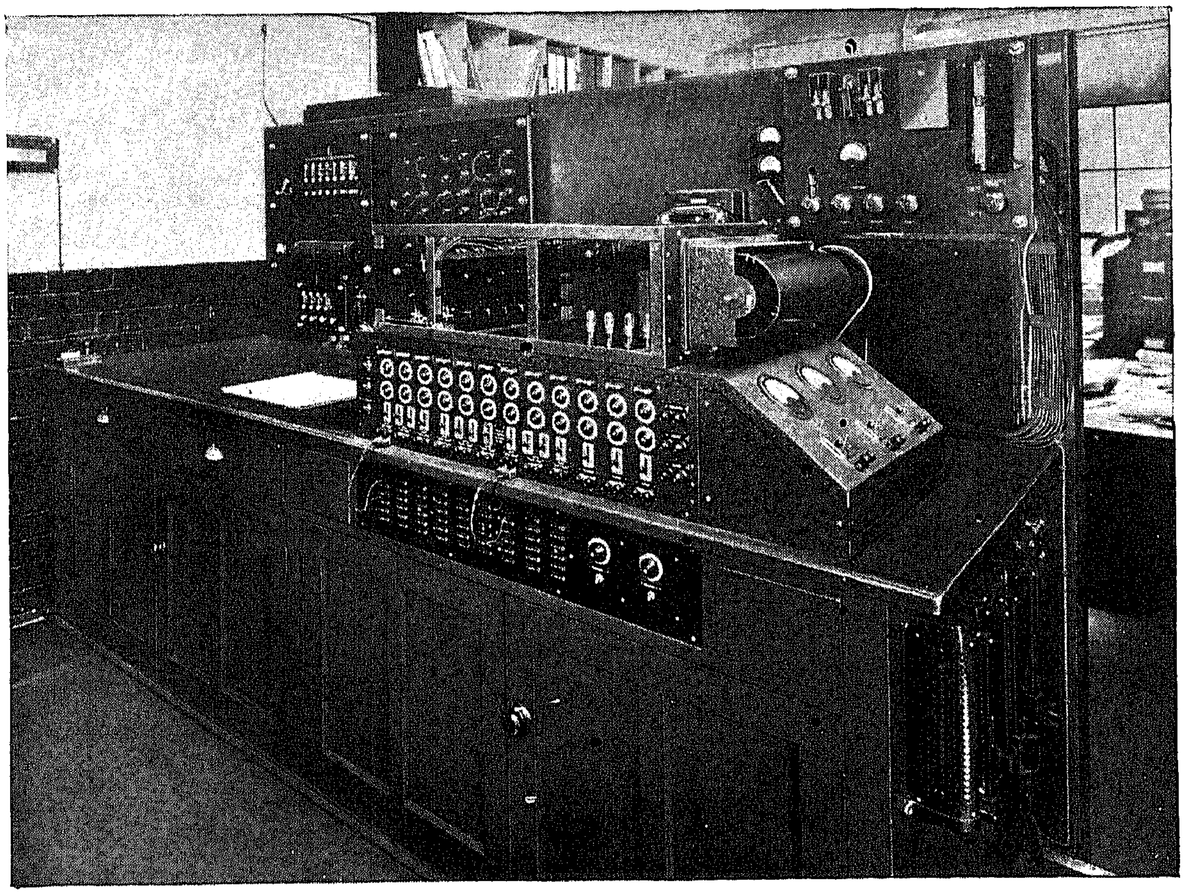


Fig. 9.—Twelve-element low-frequency oscillograph (light covers removed).

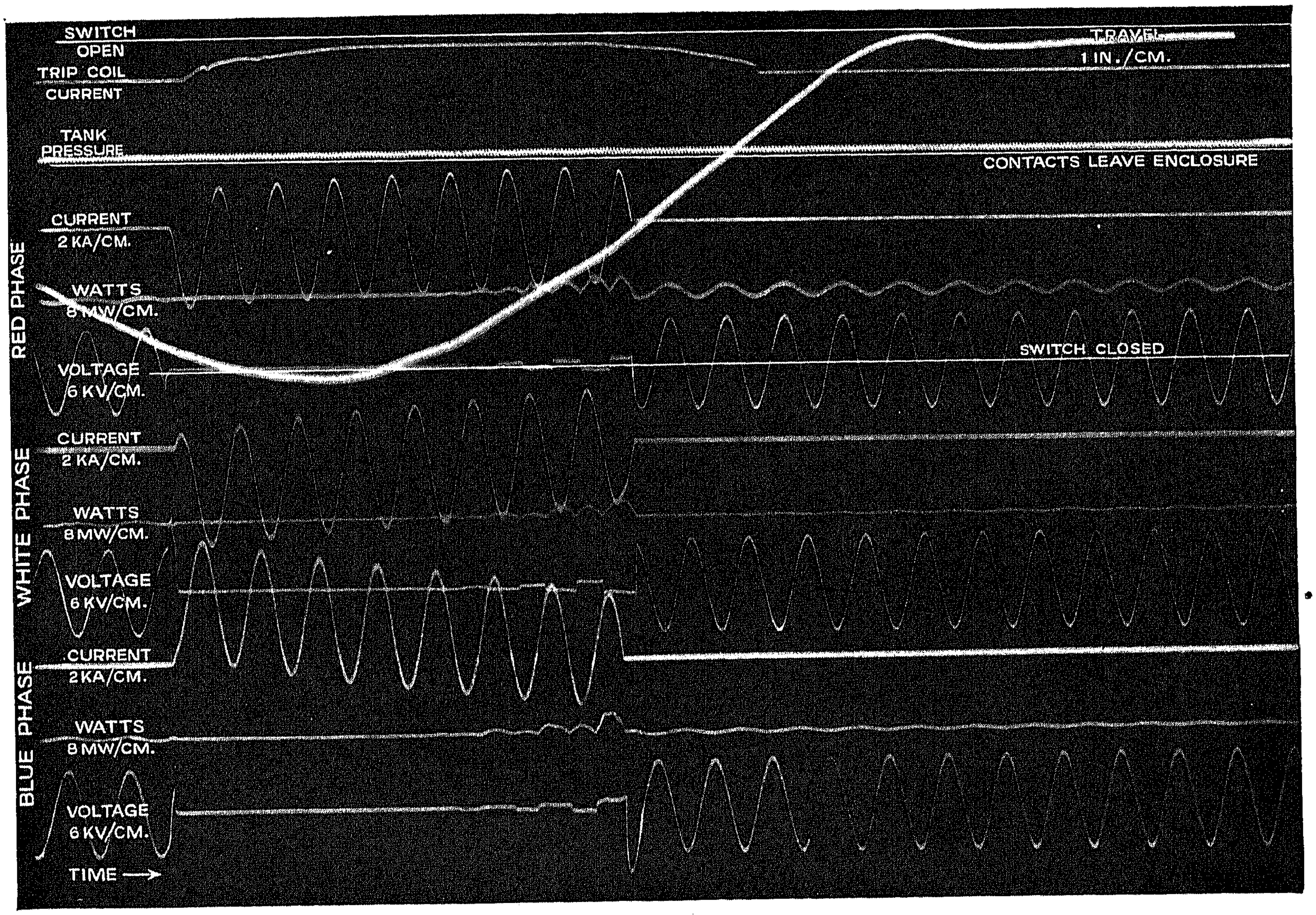


Fig. 10.—Typical oscillogram taken with the low-frequency oscillograph during a make/break test.

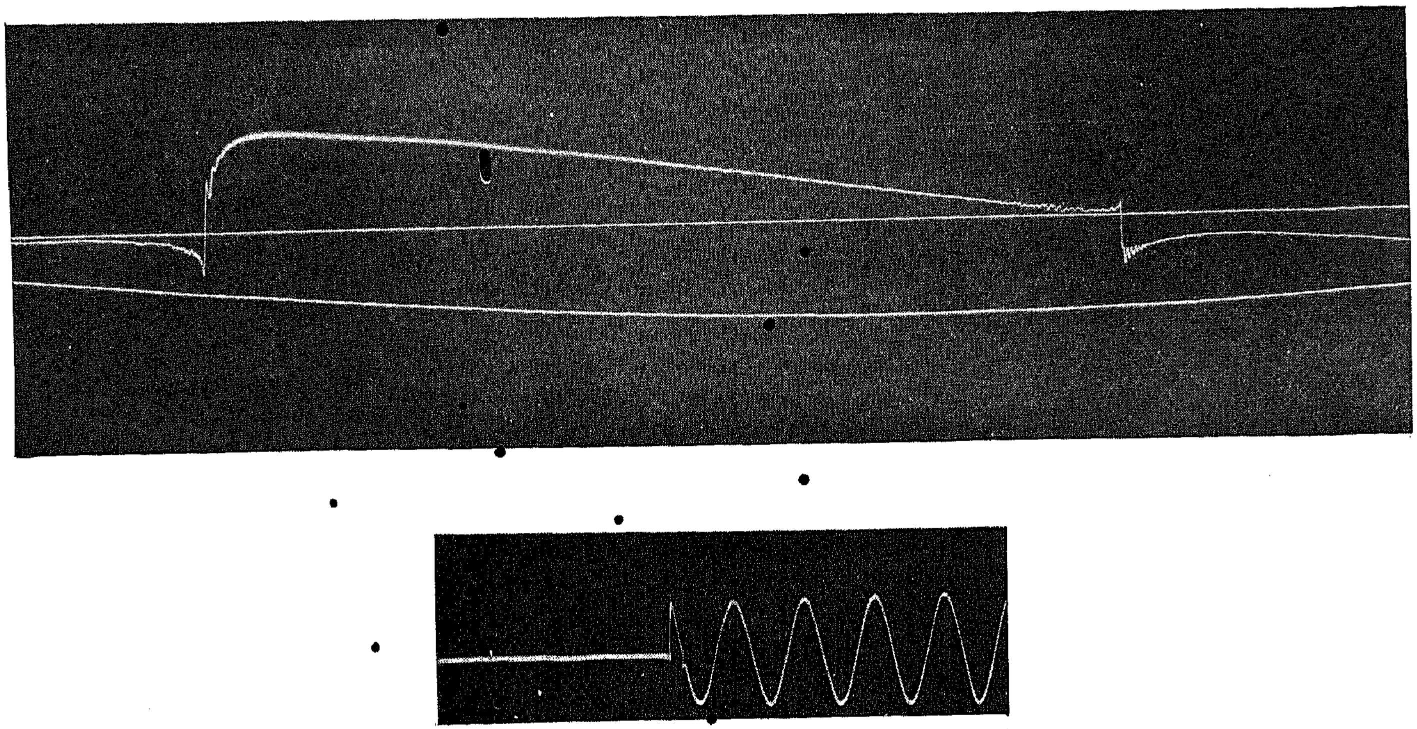


Fig. 16.—Typical recovery-voltage record taken on the single-phase cathode-ray oscillograph, together with the corresponding record taken simultaneously on the low-frequency oscillograph.

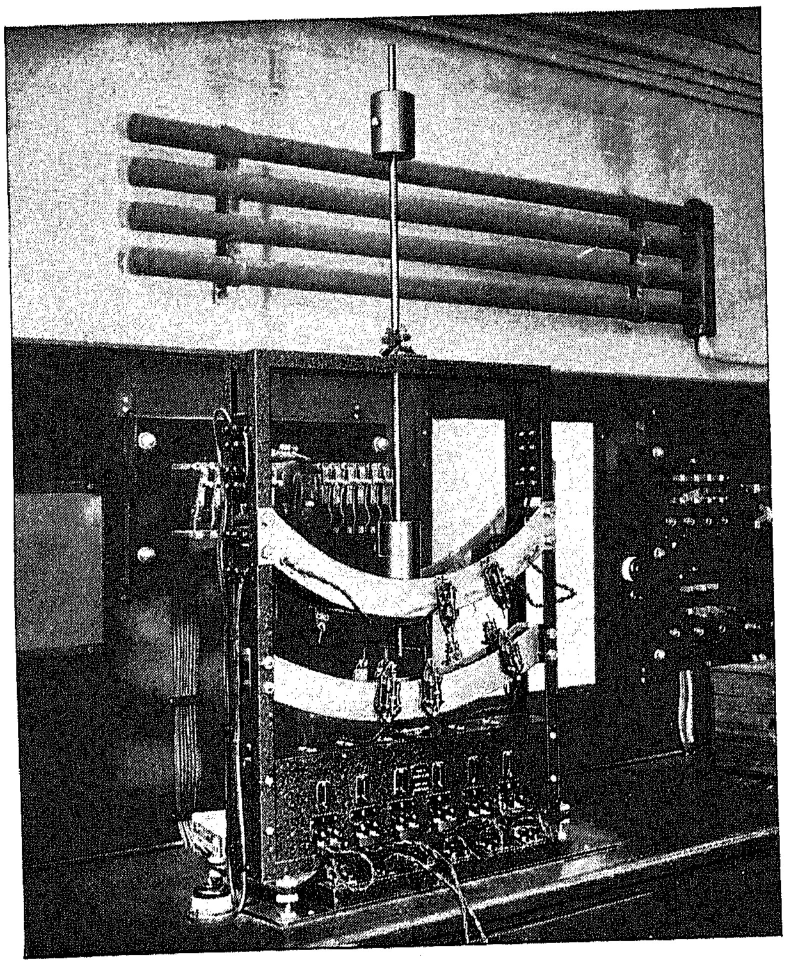


Fig. 17.—Pendulum timing controller.

voltage surges, particularly on the high-voltage side. To safeguard the generator windings from these, surge arresters are connected between the three 11-kV primary terminals and earth.

Test Bays

Two test bays have been provided for housing the apparatus while under test. The larger is suitable for circuit breakers up to the maximum size so far projected, while the smaller one is intended for apparatus rated up to 500 MVA. The walls are of reinforced concrete, and in the floors are sumps for collecting the oil discharged from switch vents. The front of each cell is left open for observation purposes, but doors remotely controlled from the observation room are provided. These are closed in the event of a serious fire.

Apart from sand buckets and hand extinguishers, two separate fire-fighting plants have been installed for use in either bay. The first consists of a bank of eight 50-lb. cylinders of carbon-dioxide gas, all of which can be released into either bay by the engineer-in-charge in the observation room. The second equipment is a " Mulsifyre " plant which, under the control of the engineer-in-charge, projects an atomized water spray on to any burning oil in the bay and by emulsification extinguishes the flames. A portable Mulsifyre nozzle is also used for extinguishing burning oil thrown on to the area in front of the cells.

The testing power is brought into the bays through robust and quickly-replaceable porcelain bushings. Earthing switches are provided on both high- and medium-voltage circuits, these being interlocked with the generator field.

To permit quick tank lowering for inspection of contacts and circuit-breaker interior between tests, each bay is provided with an electric hoist.

Oil Supplies

A constant supply of clean, dry oil is necessary for oil circuit-breakers on test. Two 3 000-gallon tanks, one for clean and the other for used oil, have been installed. The dirty oil is decarbonized and dehydrated in a Streamline filter plant. Oil from the sumps containing a larger percentage of water is initially treated in a De Laval centrifugal separator.

PART II

METERING AND INSTRUMENT EQUIPMENT

Low-frequency Oscillograph

The transient currents and voltages which occur during a short-circuit test can only be recorded by an oscillograph. The records normally taken are volts, amperes, and watts per phase, tank pressure, cross-bar travel, and trip-coil current. For special tests a greater number of records may be required. It was therefore decided to install permanently an oscillograph giving 12 records on one film, this being sufficient for routine testing, and to make arrangements for running an existing portable 6-element instrument in parallel with it, thus obtaining 18 records for special tests. Fig. 9 (see Plate 1, facing page 600) gives a general view of the 12-element oscillograph with the covers removed.

The vibrators are mounted in a double row at one end of the containing box. There are 8 permanent-magnet vibrators for recording volts and amperes per phase, tank pressure, and trip-coil current; three dynamometer vibrators for recording arc watts per phase; and one super-sensitive vibrator capable of giving a deflection of 30 cm. for recording cross-bar travel. Each unit can be easily removed for cleaning and inspection.

Four 8-volt 32-watt straight-filament gasfilled Osram lamps are used for illumination. These are connected in series and run from a 220-volt d.c. supply through a ballast resistance provided with tappings which can be cut out to boost the current during exposure. For normal ($\frac{1}{2}$-sec.) exposures the current is increased from the normal of 4 to 5 amperes, but for shorter exposures, during which the film drum is run faster and higher writing speed is required, the current can be increased to 6 amperes. Small neon indicators are connected across each lamp for rapid identification should a filament burn out. The lamps have a very long life, as they are only run for a short period during each test. Experience has fully justified the choice of light source, the gasfilled lamps requiring no attention whatsoever after they have been initially installed and adjusted. Furthermore, they enable the oscillograph to be made considerably more compact than if an arc lamp were employed, the overall dimensions of the oscillograph box (excluding film drum and resistance control board) being only 31 in. × 20 in. × 10 in.

Each lamp is housed in a separate tubular container in the end of which are arranged three small lenses, individually adjustable in a horizontal plane. The lamp houses are suspended above the centre lines of the vibrator mirrors so that the reflected beams pass beneath them into a cylindrical convex lens 14 in. long × 2 in. wide which focuses the ray into a sharp spot on the film surface.

Between the cylindrical lens and the film drum is located a shutter consisting of a slotted aluminium plate moving in vertical guides. The shutter latch is released electrically to open and close the exposure for each test, resetting being performed manually. To prevent the aluminium from becoming scored and thus sticking in the guides, the rubbing surfaces were heavily oxidized by an anodizing process in a bath of strong chromic acid.

The film drum fits on to the end of the oscillograph box in two vertical guides, and accommodates a film 19 in. long by 12 in. wide, one film being normally used for each short-circuit test. Four drums are provided to enable tests to be made in rapid succession. The cameras are removed to the dark room for loading, access to the film being gained by removing the back of the box. A lightproof shutter inside the camera box closes automatically when the drum is removed from the oscillograph. The boxes are constructed of aluminium and weigh only 5 lb. each. Hypersensitive film (speed 1 500 H and D) is used for important tests the records of which have to be copied. For experimental investigations of lesser importance recorder paper is employed.

The film drum is driven by a variable-speed d.c. motor through rubber belts and large-diameter reduction pulleys in order to provide constant and smooth speed over each revolution. A simple dog clutch is interposed to enable the camera to be removed for loading, etc. The speed range obtainable with motor speed control and alternative gear ratios is 10–480 r.p.m.; this covers all the usual exposure times required in short-circuit testing. A tachometer is attached to the drum shaft.

The camera driving shaft also carries a contact which closes for a short period once during each revolution, and this in conjunction with a high-speed relay and the pendulum timing control (to be described later) enables the record to be spaced so that it does not cross the join in the film. The contact can also be used to enable two or more tests to be recorded on one film without overlapping.

The sensitivities of the various vibrators are adjusted by non-inductive resistances provided with tappings selected by two small 10-point rotary switches. Additional series resistance can be put into the vibrator circuits when required by means of the tapped resistances let into the bench beneath the oscillograph. Small glass fuses are arranged in series with each vibrator to prevent damage to the strip in the event of an accidental overload.

Calibration of the vibrator sensitivities is most important. To enable this to be carried out before each series of tests with the minimum delay, each vibrator circuit is provided with a 2-pole change-over switch. With the switch in the lower position the vibrators are connected through a plug selector board to the shunts, potential transformers, etc., in the test circuit. In the upper position the switches connect the vibrators to the calibrating board arranged at the end of the oscillograph.

For routine checking, calibration is effected by applying measured values of volts and amperes to the vibrators through resistances which compensate for the pilot leads to the shunts or potential transformers, etc. The calibrating board is supplied from a battery, through variable slider resistances mounted on the bench-front beneath it. Links are provided for inserting portable substandard instruments for checking the three panel meters. The recording-spot deflection is measured on a graduated screen which fits into the film drum guides. For convenience in scaling the oscillograms the sensitivities of the vibrators are adjusted so that all three phases have the same calibration factor, this being made a whole number.

A typical record taken with the above oscillograph is shown in Fig. 10 (Plate 1).

Shunts

Shunts are employed for operating the oscillograph vibrators recording short-circuit current. To reduce the voltage applied to the pilots and the oscillograph they are located at the earthed star point of the test apparatus. To eliminate errors due to proximity effect and stray magnetic fields, the shunts have been made non-inductive. Fig. 11 shows the construction of the shunts for recording currents from 20 to 200 kiloamperes. Each has a resistance of 0·00005 ohm and is made of a material having a negligible temperature-coefficient. The potential leads are taped close to the outer tube in order to reduce pick-up from stray flux. The cross-section of the resistance element is 6·0 sq. in., this being sufficient to carry 200 kiloamperes for 25 cycles for 200 deg. C. temperature rise.

Three shunts similar to the above have been tested when mounted on 24-in. centres, and the total interference from adjacent circuits, etc., has been found to be less than 0·25 per cent, which, compared with the overall accuracy of oscillographic measurement, can be regarded as negligible.

Currents ranging from 0·5 to 200 kiloamperes are measured with three shunts, rated as follows: 0·5 to 10 kiloamperes (r.m.s.), 0·001 ohm; 8 to 40, 0·000125 ohm; 20 to 200, 0·00005 ohm.

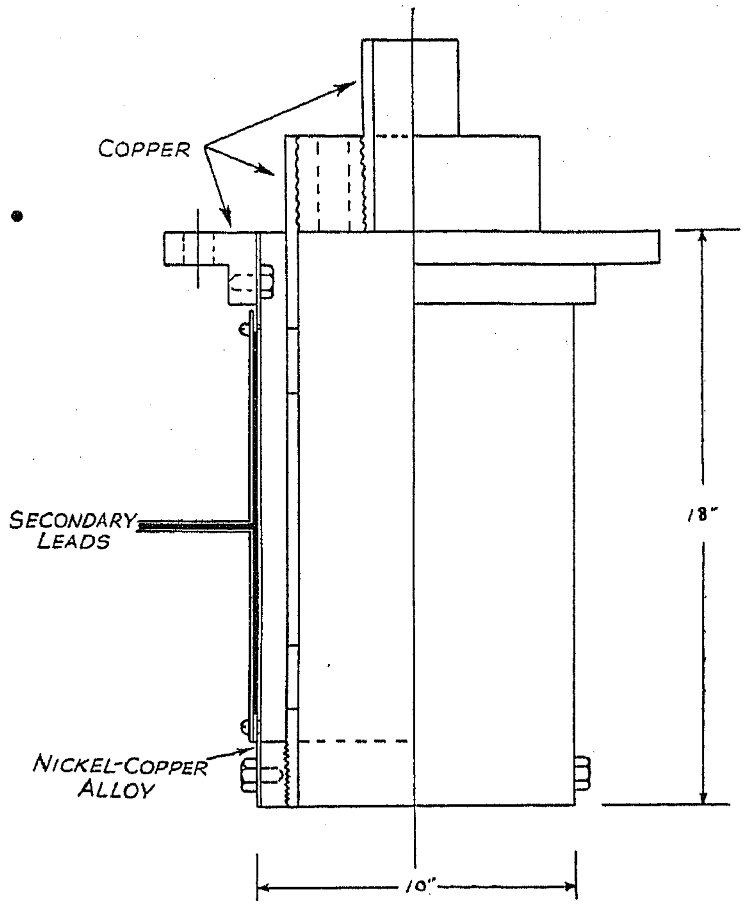


Fig. 11.—200-kA shunt.

Current Transformers

When the dynamometer oscillograph vibrators are used for recording arc watts their current coils are energized from current transformers giving a secondary output of 5 amperes.

Transformers of the ring type with evenly distributed secondary windings have been found to be quite satisfactory provided they are operated at a flux density low enough to prevent saturation by completely asymmetrical current waves. The iron circuit of the largest transformer, rated at 160 000/5 amperes, is $1\frac{5}{8}$ in. by $1\frac{5}{8}$ in., with a mean circumferential length of $52\frac{1}{2}$ in., and is built up of stalloy laminations. The primary consists of a copper tube of 10 in. diameter. The secondary winding has 32 coils of 1 000 turns each. These can be connected in series-parallel to give the ratios 160/80/40/20 kiloamperes to 5 amperes. The connections are quickly changeable by operating four switches per transformer. Owing to the large number of secondary turns the open-circuit voltage is several kilovolts. To prevent danger to personnel and damage to the secondary cables in the event of a break in the vibrator circuit, a spark-gap set to discharge at 500 volts is permanently connected across the secondary winding. Three transformers mounted side by side on 24-in. centres have been found to have negligible mutual interference. A second set of transformers, similar in design to the above, with ratios 16/8/4/2 kiloamperes to 5 amperes, are installed to enable the whole testing current range to be covered.

Potential Transformers

The generator terminal voltage is measured from three single-phase star-connected potential transformers rated at 22 kV/110 volts. Potential transformers are also provided for measuring the voltage across each pole of the test apparatus. These consist of three 11 kV/110-volt single-phase units mounted behind the test bay in the machine room and connected to either the generator or the low-voltage side of the low-voltage transformer; three 22/44 kV/110-volt single-phase transformers mounted outside and arranged for connection either to the generator or the high-voltage side of the high-voltage transformers; and one 88 kV/110-volt unit for single-phase high-voltage tests. All of the transformers are of standard design and are protected by high-rupturing-capacity fuses and series resistances.

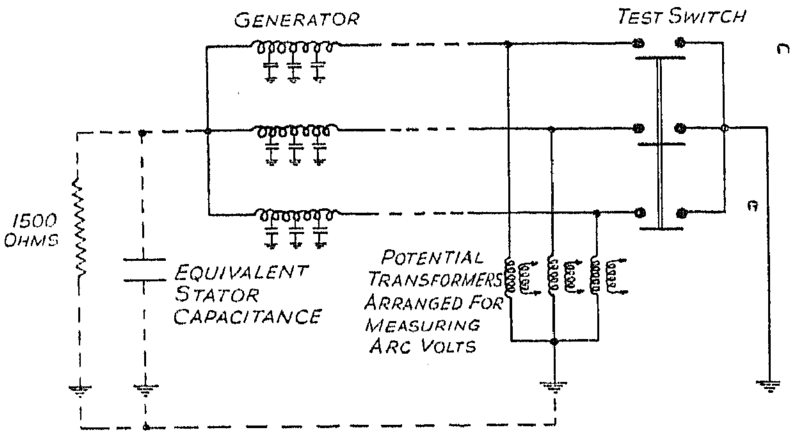

GENERATOR
TEST SWITCH
1500 OHMS
EQUIVALENT STATOR CAPACITANCE
POTENTIAL TRANSFORMERS ARRANGED FOR MEASURING ARC VOLTS

Fig. 12.—Potential transformers with insulated-neutral generator.

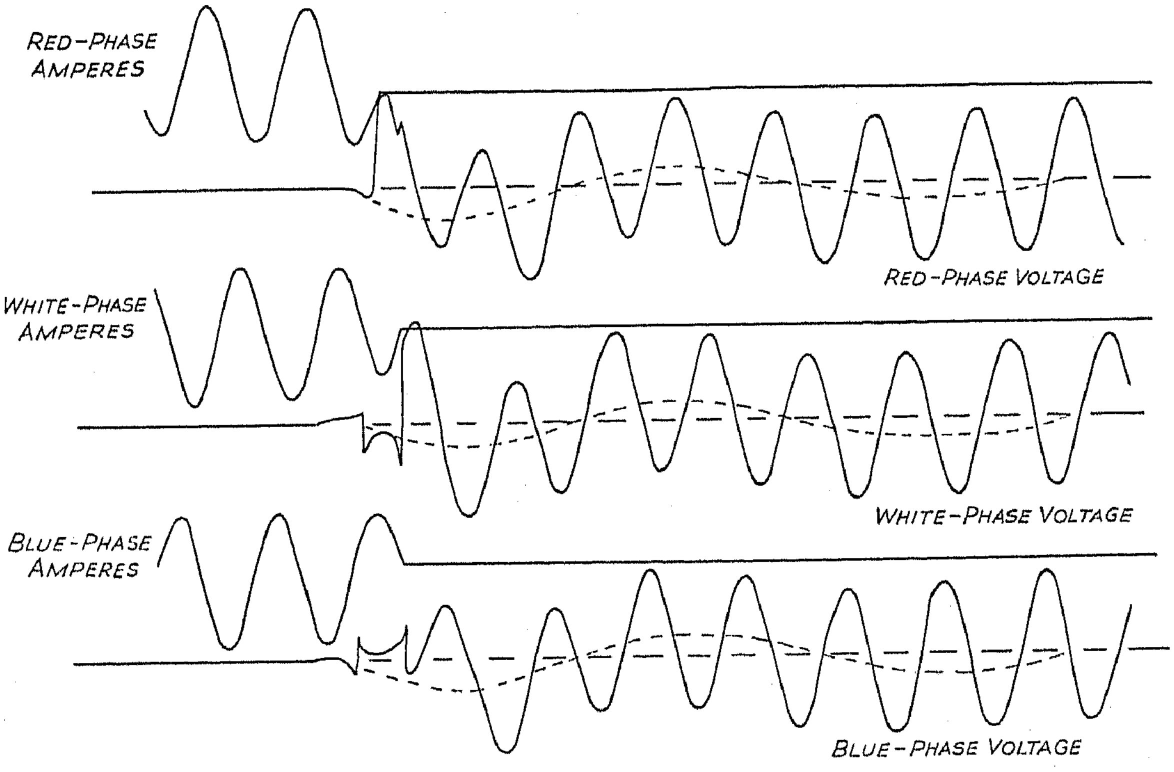


Fig. 13.—Recovery-voltage distortion with potential transformers and unearthed generator.

When testing with the generator connected in delta, or the neutral point insulated, the inductance of the potential transformers is in series with the capacitance of the generator winding to earth, as shown in Fig. 12. The natural frequency of this circuit is low (10–200 cycles per sec.), depending upon the inductance of the transformers for the particular voltage applied and the secondary burden. An effect due to this circuit arrangement is the distortion of the recovery voltage. When the first phase of the circuit breaker clears, the voltage of the generator neutral-point is raised above earth and the electrostatic capacitance of the windings is charged. Upon the other two phases clearing, the neutral point again falls to earth potential and the capacitance discharges through the potential transformers at the natural frequency of the circuit. The 50-cycle recovery voltage is thus superimposed on a low-frequency damped oscillation. An example of recovery-voltage distortion due to this is shown in Fig. 13.

There are several ways of eliminating this effect. If the generator is connected in star the neutral point can be earthed through a non-inductive resistance of about 1 500 ohms. This forms a discharge path for the winding capacitance (see Fig. 12), and has little effect upon the voltage distribution across the circuit-breaker terminals. The resistance used is made up of carbon rods mounted on a bakelite panel and oil-immersed.

When the generator is connected in delta the distortion can be obviated by using non-inductive-resistance potential dividers instead of transformers for the voltage measurement.

Potential Dividers

Three sets of 3-phase resistance potential-dividers have been installed. The circuit employed is shown in Fig. 14. The resistance of the divider is selected so that it passes about 30 milliamperes at full voltage, most of this flowing through the oscillograph vibrator. Should the vibrator become open-circuited the 1 000-ohm resistance prevents the voltage on the pilots rising above 30 volts.

The first set of dividers are suitable for use up to 4·0 kV and have a maximum resistance of 50 000 ohms with tappings at each 5 000 ohms. The resistance units used have a value of 5 000 ohms each, and consist of No. 44 S.W.G. double-silk-covered nickel-copper resistance wire wound on flat mica strips (8 in. × $1\frac{1}{4}$ in.). The units are air-insulated.

For use from 3·0 to 22 kV the dividers have maximum resistances of 250 000 ohms, with tappings at each 50 000 ohms. Fifty 5 000-ohm units are used, mounted on a bakelite framework and immersed in oil.

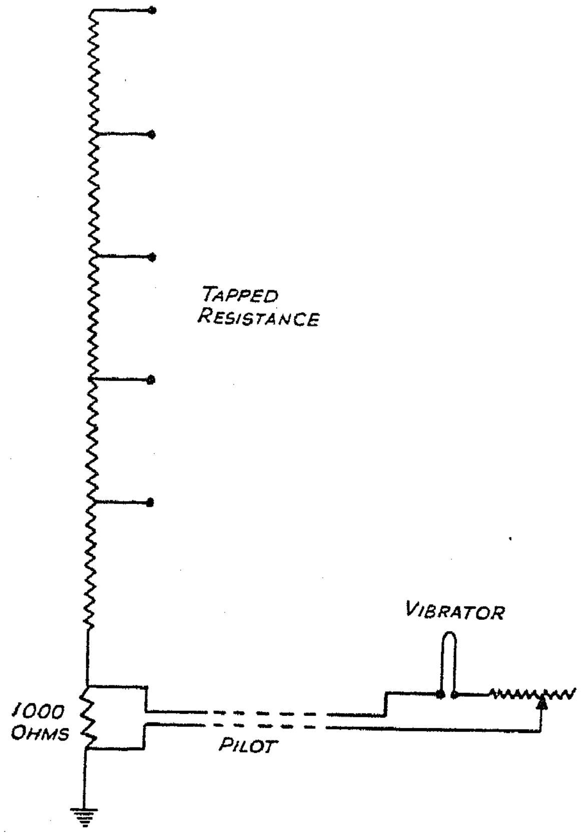


Fig. 14.—Resistance potential-divider.

The high-voltage dividers are made up in 200 000-ohm units, each consisting of a non-inductive wire-wound resistance oil-immersed within a cylindrical porcelain container fitted with flanges at each end to enable the units to be built up into suitable stacks. Twelve units are used, these being sufficient for metering up to 66 kV (3-phase), or 120 kV (single-phase).

Fluid-pressure Recorder

Records of the transient pressures exerted on the tank walls during a circuit-breaker's operation are recorded on the oscillogram in order that they may be correlated with the electrical phenomena. The scheme used is similar to that employed by Messrs. Pearce and Evans.*

The transmitter, which is bolted to the tank wall, consists of a small E-shaped laminated iron circuit with a coil on the centre limb. A circular stalloy armature is arranged so that movement of a spring-steel diaphragm by the pressure varies the impedance of the coil, which forms one arm of a simple bridge circuit supplied with low-voltage alternating current at 1 000 cycles per sec., obtained from a valve generator; with no pressure on the diaphragm the bridge is balanced and the output, which is connected to a standard electromagnetic oscillograph vibrator, is zero. The amplitude of the envelope of the record is calibrated against pressure by connecting the transmitter to a hydraulic testing pump. By selecting suitable constants the calibration has been made linear. The diaphragm has been made so that it can be easily renewed should an accidental over-pressure permanently distort it. In service the recorder has proved to be very robust, withstanding considerable ill-usage and rough treatment without serious damage. The accuracy of recording of both amplitude and waveform is easily sufficient for general tank-design calculations.

Cross-bar Travel Recorders

Two methods are used for recording the mechanical operation of the test circuit-breaker: the first photographs the travel characteristic on the oscillogram, and the other uses a separate mechanical recorder. The transmitter for the oscillographic method consists of a potentiometer, the sliding contact of which is moved by the circuit-breaker cross-bar, thus varying the voltage applied to a vibrator. Two transmitters are used, one having a travel of 12 in., the other a travel of 24 in.

In order to increase the accuracy of measurement from the record a super-sensitive vibrator is used, giving a working deflection up to 30 cm. if necessary. This increased deflection is very useful for measuring short arc lengths such as are obtained when arc-control devices are employed on the switch. A typical record is shown in Fig. 10 (Plate 1).

The mechanical recorder consists of an aluminium cylinder, 6 in. diameter by 24 in. long, to which paper can be attached, rotated at constant speed by a small electric motor. A pencil moved axially by the cross-bar marks the paper during its travel. The speed of revolution provides the time scale, from which the cross-bar velocity can be calculated. The point where the arc-tips part can be marked on the record, and by using this as a datum line it is possible to scale off the number of half-cycles arc duration as given by the oscillogram and thence find the point on the opening stroke at which extinction occurred and the corresponding arc length. A typical developed record, scaled and marked, is shown in Fig. 15. The speed of rotation is adjusted by means of a flyball governor and measured by a simple stroboscope, illuminated by a neon lamp connected across the 50-cycle operating supply. Two standard speeds of 60 or 90 r.p.m. are used.

Pilots

The pilot cables between the oscillograph and the shunts, transformers, transmitters, etc., are of screened concentric cable run as far as possible at right angles to the main busbars in order to reduce interference to a minimum; 24 cables are used.

Cathode-ray Oscillographs

Two special high-speed cathode-ray oscillographs have been installed for recording restriking-voltage characteristics. The first is a single-phase instrument similar to the one recently described by Mr. G. A. Whipple.* The discharge tube is of the cold-cathode type, and is mounted at an angle to the axis of the main body, so that the beam is normally trapped. Application of voltage to a pair of plates allows the beam to pass into the main section of the oscillograph tube housing the deflecting plates. The beam is focused by varying the current through a concentric solenoid mounted approximately midway between the discharge tube and the camera drum. The spot may be viewed and the deflection calibrated on a fluorescent screen mounted on the back of a manually operated shutter above the film. The photographic film on which the record is taken rotates at speeds up to 3 000 r.p.m. within the main vacuum of the oscillograph. The film is 12·5 cm. wide and 2 metres long, so that at full speed when one 50-cycle wave is extended to the full length of the film, high-frequency oscillations up to 200 000 cycles per sec. are readable.

---

* *Journal I.E.E.*, 1932, vol. 71, p. 713.

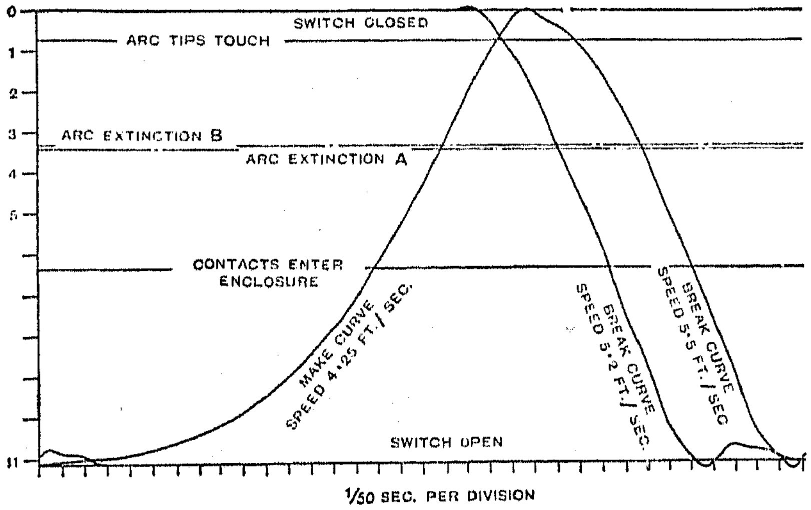


Fig. 15.—Typical oil circuit-breaker travel record showing break and make/break operations.

Ordinates represent travel in inches.

The drum is rotated by a d.c. motor, speed control from 50 to 3 000 r.p.m. being arranged. The drive is taken into the vacuum through a 2-stage gland, the intermediate section being maintained at a pressure of about 0·1 mm. of mercury by two rotary oil pumps in cascade. The main body of the oscillograph and the camera drum are evacuated to a pressure of 0·001 mm. of mercury by two 4-stage mercury diffusion pumps, which are backed by a single-stage rotary oil pump. Two traps cooled to − 60° C. by carbon-dioxide snow are situated between the oscillograph and the mercury pumps in order to condense the water vapour given off by the film, and prevent it slowing down the pumps, and also to prevent mercury vapour from passing into the oscillograph. A water-flow relay cuts off the mercury-pump heaters should the cooling-water supply fail. The film is loaded into the camera through an aperture with a removable cover sealed with a soft rubber gasket. The capacity of the pumping system is such that the time from loading the film to taking the record is about 30 minutes. This oscillograph is used principally for research work on experimental circuit-interrupting devices on which single-phase tests only are made, and Fig. 16 (Plate 2) shows a portion of a record, the low-frequency oscillogram of the same voltage taken simultaneously being included for comparison of the time scales.

The second cathode-ray oscillograph is a 3-phase model, the records of all three phases being taken on one film 36 in. long and 12 in. wide. The development of this instrument is due to Mr. R. V. Whelpton.* Three exactly similar oscillograph tubes are mounted side by side on 4-in. centres, metal discharge tubes of the cold-cathode type being employed. Surrounding each tube about halfway down is a coil for bringing the electron beam to a sharp focus at the surface of the photographic film. Below are four coils arranged so that each beam can be given independent steady deflections in two directions at right angles and thus the zero position brought to any desired point on the photographic film. Below the positioning coils are the electrostatic deflection plates, which move the beam in a direction at right angles to the rotation of the film drum. The beams are trapped prior to exposure of the film during recording, by applying a low voltage to a pair of deflection plates in each tube.

The film drum is rotated by a 2-pole induction motor arranged with the rotor within the vacuum and the stator outside, the vacuum seal consisting of a constantan tube passing through the air-gap. The film drum is enclosed within a lightproof case which can be withdrawn from the oscillograph and passed into the dark room for reloading. Two drums are provided.

The driving motor is operated from an a.c. supply the frequency of which can be varied from 20 to 100 cycles per sec. Thus at full speed the drum rotates at 6 000 r.p.m., one half of a 50-cycle wave being extended to 36 in. long, enabling 200 000-cycle oscillations to be measured.

The oscillograph is evacuated by two cascaded condensation pumps, operating with low-vapour-pressure oils, and backed by two cascaded rotary oil pumps. A carbon-dioxide snow trap is again used between the pumps and the oscillograph. Variable leaks between the discharge tubes and the backing vacuum are arranged for controlling the tube vacua. A large-bore high-vacuum valve between the condensation pumps and the oscillograph, and a bypass from the rotary pumps to the oscillograph, enable the condensation pumps to be kept working whilst films are being changed.

The high-voltage direct current for the discharge tubes of both oscillographs is obtained from a valve rectifying equipment capable of giving an output of 80 kV. The transformer of this unit is arranged so that it can also be used for taking the breakdown values of oil samples.

The cathode-ray oscillograph room is completely lined with $\frac{1}{4}$-in. steel plates to screen the instruments from interference from the heavy currents in the main circuit. To prevent moisture condensing, the walls have been sprayed with cork granules before painting. The windows are provided with lightproof shutters in order to darken the room while the single-phase instrument is being loaded.

The voltage deflecting plates, which require about 400 volts, are connected to the main circuit through capacitance potential couplers and low-capacitance air-spaced concentric cables. The use of the latter enables the capacitance of the couplers to be reduced to a minimum in order to prevent appreciable lowering of the natural frequency of the test circuit. The record distortion due to the coupler system is negligible for frequencies up to 200 kilocycles per sec. Voltage calibrations of the records are obtained from the low-frequency oscillograms taken simultaneously, the results being checked against the figures obtained by the application of known voltage to the deflection plates immediately before and after the tests.

---

* *Journal I.E.E.*, 1936, vol. 78, p. 497.

* *Journal I.E.E.*, 1936, vol. 78, p. 508; and *Journal of Scientific Instruments*, 1935, vol. 12, p. 226.

The synchronization of the cathode-ray oscillograph records with the short-circuit is obtained by operating the de-trapping circuits from the main timing pendulum through a high-speed relay, 6 cycles being an average exposure.

The time scales of the above two cathode-ray oscillographs represent the practical limit obtainable by mechanical means. While this is sufficient for the majority of investigations there are problems in connection with rates of rise of restriking voltage at abnormally high natural frequencies, such as can be achieved by mounting a portion of the circuit reactance very close to the test circuit breaker, in which a swept time-base record is necessary if reasonable accuracy is to be ensured. A third cathode-ray oscillograph is therefore in course of construction, in which the record will be taken on a stationary photographic film and an electrostatic time-base employed. This instrument will also be used in the impulse testing of transformers, lightning arresters, etc., while under full excitation; the installation of the necessary surge generator is contemplated for the near future.

Short-circuit Timing

During each test the switching of the main circuit components and the recording apparatus has to be controlled to a time schedule which must be correct to within $\frac{1}{100}$ sec. This necessitates a very accurate timing device, which should also be as flexible as possible in operation to allow for the wide range of time settings demanded by tests on various pieces of apparatus with differing characteristics. The timing controller installed consists of a series of relay contacts actuated by a compound pendulum during a single swing, and is shown in Fig. 17 (Plate 2).

Twelve contacts are provided, all arranged so that they may be either closed or opened by the action of the pendulum. Each moving contact consists of a silver ring recessed into an insulated barrel which moves axially in guides. Four fixed silver contacts are arranged to rub lightly on the barrel, the upper pair being connected together by the ring when the cylinder is latched against the operating spring. When the pendulum trips the latch, the upper pair of contacts are broken, and the lower pair are made. Since only a sliding contact is used, bounce is eliminated.

The twelve contacts are mounted on four sectors, enabling the contacts to be set at very close time-intervals if required. The pendulum has an active swing of 50°, the period of swing being varied by adding jockey weights to the lower bob. Five weights are provided, these giving swings of 1, 2, 3, 4, or 5 sec., a range which is ample for all testing requirements. To enable the pendulum contacts to be safely reset and adjusted between tests a 12-pole contactor is provided for rapidly isolating all connected circuits.

Before the test the pendulum is latched to one side, the latch being tripped by a small electromagnet energized via the contact on the main oscillograph camera drum so that the release is synchronized with the rotation of the film to ensure that the record does not cross the join.

The pendulum contacts operate as follows for a typical " make/break " short-circuit test: Contact 1 opens low-frequency oscillograph shutter; contact 2 boosts generator field; contact 3b closes test circuit-breaker; contact 4 trips test circuit-breaker; contact 5 untraps cathode-ray oscillograph beam; contact 6 traps cathode-ray oscillograph beam; contact 7 closes low-frequency oscillograph shutter; contact 8 opens generator field; contact 9 trips master circuit-breaker; contact 10 opens test oil circuit-breaker closing-coil circuit. Contact 3a closes maker switch (alternative for contact 3b above on " break " tests); contact 11, spare.

As each circuit breaker tested has different operating time-delays it is necessary to measure these before the short-circuit time schedule can be arranged. To enable this to be done quickly, a simple and robust " cycle counter " has been made. It is operated from a 230-volt 50-cycle controlled-frequency supply, and consists of a scale, graduated from 0 to 50, rotated by a standard telephone rotary-switch mechanism energized through a half-wave metal rectifier. Connections are made to the test circuit-breaker so that by opening and closing it the operating delays can be read off in cycles, which is sufficiently accurate for all routine testing.

Other Apparatus

A standard 16-mm. cinematograph camera, remotely controlled from the observation room, is used for recording special tests and is very useful for confirming visual observation of smoke and flame emission. A standard half-plate camera is used for photographing the interiors of circuit breakers before and after important tests. To assist in the interpretation of the cathode-ray oscillograms a knowledge of the natural frequencies present in the test circuit is very useful. Several frequencies may appear, since the generator, reactors, transformers, busbars, etc., all have different frequencies. The frequency response of the various test-circuit set-ups is measured by applying a small voltage derived from a variable-frequency oscillator (range, 20–200 000 cycles per sec.), and observing the volt-ampere characteristic by means of a gas-focused cathode-ray oscillograph. A portable universal bridge is also used for measuring the various inductances, capacitances, and resistances, so that the measurements may be amplified by calculation.

Acknowledgments

The author is indebted to the General Electric Company for permission to publish details of their Laboratory, and desires to thank Dr. C. C. Garrard and Dr. William Wilson for their encouragement in writing the paper, together with his colleagues, Messrs. K. B. Wood and W. S. Thomson, who have assisted in its preparation.

DISCUSSION BEFORE THE NORTH MIDLAND CENTRE 19TH JANUARY, 1937

Mr. W. Dundas: Prior to the introduction of switch-testing stations reliance had to be placed on empirical formulae and experience in the field for the developments in the design of heavy switchgear. This method has led to fallacious and optimistic estimates of switch ratings, rendering it necessary, after subsequent tests, to modify the original rating. The work of research now made possible has considerably improved the technique employed in the design and manufacture of switchgear and other associated equipment, which is very necessary to meet the exacting demands of the industry to-day. From the users' standpoint the testing of switchgear is equally important, and establishes confidence that the equipment supplied is up to the required standard for the particular duty it may be called upon to perform.

In the Home Office Report on Electrical Accidents in 1935 a switch is stated to have failed on a lower duty than that for which it had been tested, and this raises the question whether the tests carried out at the testing station represent conditions that may obtain in service. It would appear that further research is required before the question can be answered satisfactorily. The failure referred to above may have been due to some defect in the switch or to the method of operation, and without full details of the conditions appertaining to the case it is not possible to form a definite conclusion on the subject.

In his opening remarks the author referred to the use of compressed air for the closing of circuit breakers, and I should like to know the reason for his apparent preference for pneumatic control.

Mr. W. Fordham Cooper: I am very interested in this paper since I was for some time associated with the original circuit-breaker tests carried out by the E.R.A. soon after the War. The developments and elaboration which have occurred since that date are very striking, but the discoveries of recent years have not been altogether unexpected. For example, I remember discussing with Dr. Whitney whether the recovery transient reached values which the low-speed magnetic oscillograph would not record. We have had to await the perfecting of more delicate apparatus to confirm this point.

At present engineers are anxious to ascertain whether test results truly represent service conditions: it has been suggested that circuit breakers on test are tuned up like a racing motor-car, whereas gear in use may be compared to last year's model—just ready for exchanging. It might be interesting to test more switches direct from service without changing the oil or making any adjustments.

There are two points on which I should like the author's opinion. In testing, the circuit breaker is usually closed into a dead short-circuit. Would it be useful to try the effect of including an arc in the circuit, as this more closely resembles the conditions of service, and may perhaps affect the operation?

Secondly, I have on several occasions found clear evidence that a high-resistance fault has developed into a dead short-circuit when the switch was approaching the fully open position. This is believed to impose a very severe duty on the breaker. How should such a condition be represented in test procedure?

Mr. W. T. J. Atkins: I should like to point out that on test plants as now constructed the rate of rise of restriking voltage is much higher than is experienced under service conditions. I have discussed this question with engineers associated with testing plants. They have assured me that to install equipment which would enable the restriking rate to be adjustable to such an extent that service conditions in that respect would be reproduced would be an expensive matter—in fact, it might cost as much as the testing plant itself. There are three testing stations in this country and, for commercial reasons, no doubt, collaboration is rather impracticable, but it does seem a pity that capital should be spent in that way when co-operation between the constructors of such equipment might, by means such as I have referred to, result in tests far more closely resembling service conditions.

Mr. R. M. Longman: The author shows an oil reservoir in the machine room 30 ft. high, from which a small pipe comes down. Does this pipe come straight down into the room, or outside? There should be some means whereby, in the event of the pipe breaking, the oil flow would be immediately cut off.

I am pleased to note that a spark-gap is provided across the secondary terminals of the author's current transformers. Are these transformers made with silicon iron or with one of the special high-permeability alloys?

Were not some troubles experienced in obtaining films for the cathode-ray oscillograph which would stand up to the high speed under the high electric stress which is employed?

It is most necessary that there should be real co-operation and collaboration between the various testing stations, so that a manufacturer or user may be sure of getting similar results from two or three stations when testing the same apparatus.

Many years ago, when I was doing some work with oscillographs, one of the best spot lights was that obtained by using the old Nernst burners.

The author mentions that the power factor on test is generally below 0·1. I am not sure whether this always gives the most severe test. I should like to know whether the author has carried out any tests with a power factor as high as 0·5. Such a value is possible on a large transmission system under fault conditions.

Mr. H. H. Ryder: I should like to know why the author uses both current transformers and shunts.

Also, with regard to the oscillograph, is there a control on the pendulum relay to trap the beam at the end of the operating sequence?

Regarding the actual generators and exciters, it seems that trouble is taken to maintain the kVA in the breaker during a test. The driving motors, however, are switched off during a test. Why not leave them connected? According to the author the fall in speed is not great, and it would therefore seem that not too great a load would be thrown on the supply. To leave the motors connected would help to maintain the speed of the machines and presumably keep the power up.

Mention has been made in this discussion of various lamps which have been tried for oscillographs. Filament lamps when over-run to the extent mentioned by the author have a higher actinic value than normally, and would possibly be more effective than the Pointolite lamp, without coming up to the standard of the arc lamp. In the Pointolite lamp the source of light is not of specially high temperatures like the arc.

Mr. W. D. Redfern: Are the breakers always tested by being completely short-circuited on the load side? In actual practice there may be some impedance not short-circuited on the load side which will affect the results. For example, in a breakdown on a 132 000-volt overhead line the arc-breaking capacity of a breaker depends upon other factors besides current values.

Mr. S. R. Arnot: Is there a means of varying the time-interval between tripping off the supply and applying the fault?

Mr. J. S. Cliff (*in reply*): The very important question of the relation between the severity of short-circuits occurring in service and those obtainable in the laboratory has been raised by Mr. Dundas and several other speakers. The factors which influence the severity of a test are, briefly, (*a*) current value, (*b*) recovery voltage, (*c*) power factor, (*d*) d.c. component of current, (*e*) natural frequency of circuit. Regarding (*a*), there is no difficulty in obtaining in the laboratory currents corresponding to any short-circuit up to 1 500 MVA. As regards (*b*), little reliable data has been published regarding the values of recovery voltages obtainable on modern interconnected systems, but in general faults up to 500 MVA will have at least 95 per cent recovery voltage, this value tending to fall somewhat for higher-capacity faults. Up to 750-MVA 3-phase short-circuits it is possible to obtain in the laboratory a recovery voltage very nearly equal to that met with in service, but above that capacity a single machine, even when using super-excitation, cannot give a recovery voltage as high as a power-station circuit fed by several large generators. In general, however, owing to the relay time-delays on the power-station circuit the fault persists for a longer time than on the test plant, and this lowers the service recovery voltage, so that even for faults from 1 000 to 1 500 MVA the laboratory recovery voltage is probably not less than 75 per cent of the service value. Dealing with (*c*), by using the resistors in the laboratory circuit there is little difficulty in varying the power factor of the applied short-circuits over a wide range, the maximum power factor being about 0·95 and the minimum about 0·03, depending upon the MVA. Tests at low power factor are more severe on the circuit breaker, and, as in service on the majority of systems full-power 3-phase short-circuits have a low lagging power factor, rupturing tests are usually made with a power factor of less than 0·1. With reference to (*d*), the value of the d.c. component of current is controlled in the laboratory by selecting the point on the d.c. decrement curve at which the circuit-breaker contacts are opened. In service, owing to relay time-delays, it is probable that the value of the d.c. component in the current broken is always low. Tests are therefore made in the laboratory with d.c. components of less than 20 per cent. There is, however, the possibility mentioned by Mr. Fordham Cooper that a circuit breaker may commence to open on an earth fault limited by an earthing resistance and the fault develop into a full-power 3-phase short-circuit before the circuit is cleared, giving considerable d.c. component in the current broken. In order to imitate this occurrence in the laboratory the circuit-breaker trip is energized very early (possibly before the short-circuit is applied by the maker switch), so that when the arc contacts part there is a considerable percentage of direct current in the current.

Factors (*b*), (*c*), and (*d*), namely recovery voltage, power factor, and d.c. component, control the amplitude of the restriking-voltage transient; factor (*e*), namely natural frequency of circuit, affects the time taken by the restriking-voltage transient to attain its maximum amplitude—the higher the frequency the faster the rate of rise of voltage. The natural frequency of any circuit depends upon the relative magnitudes of the inductance and the capacitance. Now for the same value of short-circuit current the inductance of the service circuit will be approximately the same as that of the laboratory circuit; hence the natural frequencies will be dependent upon the capacitance of the circuits alone—the smaller the capacitance the higher the natural frequency. Now, comparing the laboratory circuit with the usual power-station layout, it is obvious that the former with its very short air-spaced conductors must have considerably less capacitance to earth than the longer conductors, cables, etc., usually found on power systems; its natural frequency is therefore much higher, being about 60 000 cycles per sec. for the standard 11-kV test circuit. The rate of rise of restriking voltage is not solely dependent upon the total circuit inductance, but is influenced by the proximity of reactance to the circuit breaker. It is thus possible to find circuit breakers located in service close to a reactor or transformer in which the rate of rise of restriking voltage is abnormally high, being even greater than is obtainable on the standard laboratory circuit. These conditions can be imitated in the laboratory if necessary by mounting a portion of the circuit reactance in the test bay with the circuit breaker and using a connecting lead with the minimum capacitance. Portable reactors are available for special tests of this nature. In general, owing to the increased natural frequency of the laboratory circuit, even at high powers where the recovery voltage may be slightly lower than in service, tests are more onerous than corresponding short-circuits in the large majority of service locations.

Reliable data concerning the recovery-voltage factors, natural frequencies, and rates of rise of restriking voltage, obtained on representative supply systems, are very urgently needed so that a complete comparison can be made between service faults and laboratory tests. To measure the characteristics of a supply system involves either subjecting it to short-circuits and measuring with a portable cathode-ray oscillograph similar to that used by the E.R.A.* the rates of rise of restriking voltage obtained, or making a section dead and measuring the natural frequencies with a frequency bridge or restriking-voltage indicator.† Both of these methods cause inconvenience to the supply authorities, but the information gained by such tests on representative systems would be invaluable to the industry. Tests of this nature will have to be carried out before a testing specification giving standardized severity conditions can be compiled.

It is not so difficult as Mr. Atkins suggests to vary the rate of rise of restriking voltage obtained in the laboratory. By connecting condensers across the reactors it is possible to reduce the rate of rise to any degree; a bank of condensers has recently been installed in the laboratory described to enable tests to be made under conditions equivalent to differing service conditions, so that the effect upon the performance of various types of circuit breaker can be studied.

---

* *Engineer*, 1936, vol. 161, p. 52.

† H. Trencham and K. J. R. Wilkinson: *Journal I.E.E.*, 1937, vol. 80, p. 460.

Pneumatic operation of very large circuit breakers enables the closing delay to be made less than with electrical operation (where the large closing solenoids have a long time-constant), this being a considerable advantage for synchronizing purposes. The large closing pull required to close heavy-current circuit breakers against the electromagnetic forces produced on short-circuit can also be more easily obtained by compressed-air operation. Where a bank of circuit breakers is installed the cost of the necessary compressor is not important. In the present instance the design of circuit breaker most suitable for use as a master circuit-breaker embodied pneumatic operation, and the compressor was a necessary part of the installation for operating pneumatic circuit breakers under test.

The oil reservoir referred to by Mr. Longman is situated outside the machine room on the roof; the feed pipe is 3½ inches diameter, and runs down outside the building. There is a valve to cut off the oil supply in the event of a pipe breakage. The current transformers have silicon-iron cores. Photographic film of 0·003 in. thickness has been found to be quite satisfactory for the high speeds required in the cathode-ray oscillographs, and films seldom break provided they are carefully loaded, with due allowance for the contraction which takes place when the water vapour is removed by the vacuum. Both current transformers and shunts are not essential, but the metering is rendered more flexible by having both available. It is possible to dispense with the current transformers and to energize the field coils of the oscillograph power vibrators from voltage transformers, connecting the strip of the power vibrator in series with the current recording element supplied from the shunt. This, however, complicates the use of high-resistance potential dividers, which, as explained in the paper, are used to eliminate undesirable oscillations of the recovery voltage. The beams of the cathode-ray oscillographs are trapped after a preselected number of cycles by the pendulum timing controller.

With regard to Mr. Ryder's question of tripping out the driving motor before applying the short-circuit, reference to Fig. 4 shows that, quite apart from the slowing-up of the rotor due to the short-circuit losses, the driving motor would be seriously overloaded by the increase of the field when super-excitation is used. The decrease in speed of the rotor is governed by the kilowatts absorbed in the short-circuit, which depend upon the power factor of the circuit and the resistance of the arc in the circuit breaker. Whereas on a successful test even at high power the fall in speed over the short-circuit time might be about 5 per cent, if the test were a failure the energy liberated in the resultant continuous arc might slow up the rotor by 20 per cent. No provision is made for varying the time-interval between tripping out the driving motor and applying the short-circuit; there is, however, an interlock which prevents the fault being closed while the driving motor is still connected.

DISCUSSION ON "THE PROPERTIES OF A DIELECTRIC CONTAINING SEMI-CONDUCTING PARTICLES OF VARIOUS SHAPES"*

Mr. S. N. Ray (*communicated*): Has the author's attention been drawn to a paper by H. H. Race† on the capacitance and loss variations with frequency and temperature in composite insulation? Race experimented with laminated synthetic resin with semi-conducting liquids in pockets, and also with semi-conducting liquids enclosed in quartz or glass tubes. He concludes that it seems probable that, in synthetic resin laminated products, semi-conducting materials in small insulated pockets or fibres can account for the observed characteristics and can be represented mathematically by the Maxwell–Wagner theory. My interest in this type of dielectric was aroused by the high values of tan δ obtained, these being of the same order as those for aluminium electrolytic condensers.

Mr. R. W. Sillars (*in reply*): The experiments described by Race, in the paper to which Mr. Ray refers, certainly support the idea that dielectric loss in composite materials is due, partly or wholly, to islands of volatile conducting material. From the nature of Race's discussion and experiments, however, it would seem that conclusions from his paper can only be drawn in very general terms. There is no discussion of whether Wagner's relations between the quantity and properties of the conducting impurity, on the one hand, and the magnitude and frequency range of the dielectric loss on the other, can represent "mathematically" the experimental results. Indeed, Wagner's equations do not appear in the paper. The only quantitative agreement between calculation and experiment was obtained from a simple model of two dielectrics in series in a concentric cylindrical condenser, and not from anything resembling either Wagner's model or a real dielectric. The importance of extending Wagner's model to include considerations of shape could not have been brought out by Race's experiments with concentric condensers or with tubes of liquid placed perpendicular to the field, but the effects of fine conducting channels parallel to the field are bound to make themselves felt in actual insulators.

---

* Paper by Mr. R. W. Sillars (see page 378).

† *Transactions of the American I.E.E.*, 1933, vol. 52, p. 682.

CONTROL OF WIRELESS SIGNAL VARIATIONS

By A. L. GREEN, M.Sc., Ph.D., Associate Member, and GEOFFREY BUILDER, Ph.D.

(*Paper first received* 24*th December*, 1935, *and in final form* 23*rd June*, 1936; *read before the* WIRELESS SECTION 6*th January*, *and before the* NORTHERN IRELAND SUB-CENTRE 16*th March*, 1937.)

SUMMARY

The paper describes an experimental investigation, for simple conditions of short-distance propagation, of fading control of radio signals by methods which rely on transmission being made on adjacent frequencies. It has been found that the frequency separation of the signals required for optimum fading control is determined by the path-difference between the ground and sky rays and is independent of the mean frequency of the wave.

In general it is necessary to read messages on such circuits by observing the change in direct current in the detector at the receiver, since the audio-frequency components are uncontrolled.

Applications of the system of fading control are suggested in connection with ionospheric research, direction-finding, and broadcast telegraphy and telephony.

The most satisfactory type of controlled transmission involves suppressed-carrier technique. The use of this system in short-distance propagation ensures that the night-time signal never falls below that due to the ground ray alone. In long-distance transmissions, to be described later, the effect of the control is to remove the deep troughs of fading.

TABLE OF CONTENTS

(1) Introduction.
(2) Theory of System (*a*).
(3) Experimental Investigation of System (*a*).
(4) Theory of System (*b*).
(5) Experimental Investigation of System (*b*).
(6) Fading of Audio-frequency Components in System (*a*).
(7) Fading of Audio-frequency Components in System (*b*).
(8) An Application to Ionospheric Research.
(9) Application to Direction-finding.
(10) Applications to Broadcast Telegraphy and Telephony.
(11) Conclusions.
(12) Acknowledgments.

(1) INTRODUCTION

It is well known that it is possible to control the variations in intensity of radio signals in long-distance communication by combining the effects of two or more signals which have been transmitted on adjacent frequencies.[*]

T. L. Eckersley[†] has advocated the use of multi-frequency transmissions and has outlined a simple theory by which the optimum frequency separation can be calculated, it being shown that the path-lengths of the received sky rays determine this quantity. In the application of his system to the beam telegraphic services,[*] however, the true criterion of optimum frequency separation seems to have been overshadowed by the need for selecting frequencies whose separation was appropriate to the decrements of the tuned circuits in the receiver and to the telegraphic speed required. Under these somewhat arbitrary conditions, Wells found that a modulated carrier generally gave better results than an unmodulated one but that the reverse might be the case when the fading was slow.

Somewhat similar partially satisfactory results must apparently have been obtained by Bohm,[†] since he came to the conclusion that better fading control could be achieved by wobbling the carrier frequency[‡] than by imposing amplitude modulation.

It is therefore apparent that a satisfactory technique for communication on spaced frequencies has not yet been developed. The object of the present paper is therefore to investigate the problem more fully, beginning with short-distance propagation, in which the related ionospheric effects are well understood. The extension of the method of fading control to long-distance propagation[§] can then be attempted with the help of a theory which has been verified under easily-regulated experimental conditions.

Eckersley pointed out that the most obvious way of producing multi-frequency transmissions is to modulate the amplitude of the carrier wave at an audible frequency, thus producing two side-bands equally spaced from the carrier. Investigation of this arrangement, however, which the present authors have called "system (*a*)," has disclosed the fact that complete control of fading is not possible with simple amplitude modulation. One of the conditions for optimum control is that the carrier should be modulated to a depth of 100 per cent, and, even when this somewhat exacting requirement is fulfilled, it is found that the fading fluctuations cannot be reduced to less than one-third of their normal value. Theory and experiment agree on this point, but it has been found that full control of fading can be achieved if the carrier is suppressed at the transmitter and only the two side-bands are emitted.

Suppressed-carrier technique, referred to in this paper as "system (*b*)," has been used in preference to system (*a*) throughout the authors' recent long-distance experiments.

(2) THEORY OF SYSTEM (*a*)

In the modulation arrangement of T. L. Eckersley, a carrier wave of angular radio frequency ω_r is modulated to a depth Q at an angular control frequency ω_q. Three waves are emitted at angular frequencies ω_r, $(\omega_r + \omega_q)$, $(\omega_r - \omega_q)$, and the signal at the receiver due to the ground wave alone is, in the case of short-distance propagation,

---

[*] British Patent No. 277426—1926 (Standard Telephones and Cables, Ltd.).

[†] *Journal I.E.E.*, 1929, vol. 67, p. 992.

[*] N. WELLS: *Marconi Review*, July and September, 1930.

[†] *Telefunken Zeitschrift*, 1929, vol. 10, p. 9.

[‡] German Patent No. 314343—1928 (Telefunken Gesellschaft).

[§] A. L. GREEN and O. O. PULLEY: "Control of Phase-Fading in Long-distance Radio Communication" (see page 623).

$$e_g = \epsilon_0\left\{\sin \omega_r t + \frac{Q}{2}\left[\sin (\omega_r + \omega_q)t + \sin (\omega_r - \omega_q)t\right]\right\}$$
$$\equiv \epsilon_0(1 + Q \cos \omega_q t) \sin \omega_r t \quad . \quad (1)$$

where ϵ_0 is the vertical electric force in the ground wave. The signal due to the sky wave is, after allowing for reflection at the ground,

$$e_s = 2\epsilon_s \sin (\omega_r t + \theta) + 2\epsilon_s\frac{Q}{2}\left\{\sin \left[(\omega_r + \omega_q)t + \theta'\right]\right.$$
$$\left. + \sin \left[(\omega_r - \omega_q)t + \theta''\right]\right\} \quad . \quad (2)$$

where ϵ_s is the vertical component of electric force in the sky ray and θ, θ', θ'', are the phases between ground and sky rays of angular frequencies ω_r, $(\omega_r + \omega_q)$, $(\omega_r - \omega_q)$ respectively.

In order to evaluate the phases we make use of the following considerations. If D is the optical path-difference between ground and sky rays at an angular frequency ω_r, it is known that

$$\theta = - \omega_r D/c \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where c is the velocity of propagation. Hence at angular frequency $(\omega_r + \omega_q)$ the phase difference is

$$\theta' = \theta + \omega_q\frac{d\theta}{d\omega_r} \quad . \quad . \quad . \quad . \quad . \quad (4)$$

But $$\frac{d\theta}{d\omega_r} = - \frac{1}{c}\left(D + \omega_r\frac{dD}{d\omega_r}\right) \equiv - \frac{D'}{c} \quad . \quad . \quad (5)$$

where D' is the equivalent* path-difference between ground and sky rays. If we now define

$$\chi = - \omega_q D'/c \quad . \quad . \quad . \quad . \quad . \quad (6)$$

we have conveniently that

$$\left.\begin{aligned}\theta' &= \theta + \chi\\ \theta'' &= \theta - \chi\end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

and

Expression (2) for the sky-ray signal at the receiver then reduces to

$$e_s = 2\epsilon_s\left[1 + Q \cos (\omega_q t + \chi)\right] \sin (\omega_r t + \theta) \quad . \quad (8)$$

and then the combined signal due to ground and sky rays is

$$e = \epsilon_0(1 + Q \cos \omega_q t) \sin \omega_r t$$
$$+ 2\epsilon_s\left[1 + Q \cos (\omega_q t + \chi)\right] \sin (\omega_r t + \theta) \quad . \quad (9)$$

If the receiver includes a square-law detector, the d.c. component of the change in anode current is proportional to

$$(\epsilon_0^2 + 4\epsilon_s^2)\,(2 + Q^2) + 4\epsilon_0\epsilon_s(2 + Q^2 \cos \chi) \cos \theta \quad . \quad (10)$$

There are also audio-frequency components of current in the detector circuit but their consideration will be left to a later section. As to the d.c. component, it is apparent that fading fluctuations in it are chiefly due to variations of $\cos \theta$ and, to a lesser extent, to intensity changes of ϵ_s^2. Hence any adjustment of the modulation frequency which will make the second term in (10) small will improve the constancy of signal. The condition for fading control is therefore seen to be that $2 + Q^2 \cos \chi$ should have a mimimum value, and this occurs when

$$Q = 1 \quad \text{and} \quad \cos \chi = - 1 \quad . \quad . \quad . \quad (11)$$

leading to a value of the modulation frequency for fading control given by

$$\frac{\omega_q}{2\pi} = \frac{(2n + 1)}{2}\cdot\frac{c}{D'} \quad . \quad . \quad . \quad . \quad (12)$$

where n is an integer. The control frequency is therefore determined by the single variable D' and is independent of the mean frequency of the wave except so far as D' is a function of ω_r.*

A deduction to be made from (12) is that the odd harmonics of the fundamental control frequency are also effective for fading control. This property of the system will be discussed later, since it may be important in telephony.

If we now define, for convenience,

$$a = 2\epsilon_s/\epsilon_0 \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

as a measure of the relative intensities of the ground and sky rays, and also

$$A = \frac{I^2_{max.} - I^2_{min.}}{I^2_{max.} + I^2_{min.}} \quad . \quad . \quad . \quad . \quad (14)$$

as the amount of fluctuation in amplitude of the signal, where $I^2_{max.}$ and $I^2_{min.}$ are respectively the maximum and minimum values of the detector current, then we have

$$A = \frac{2a(2 + Q^2 \cos \chi)}{(1 + a^2)\,(2 + Q^2)} \quad . \quad . \quad . \quad (15)$$

After imposing the conditions (11) for fading control,

$$A_c = \frac{1}{3}\left[\frac{2a}{(1 + a^2)}\right] \quad . \quad . \quad . \quad . \quad (16)$$

On the other hand, for an unmodulated wave, where $Q = 0$, we have

$$A_u = \frac{2a}{1 + a^2} \quad . \quad . \quad . \quad . \quad . \quad (17)$$

so that the controlled fluctuations are reduced to one-third† of those which would have been experienced with an unmodulated wave.

(3) EXPERIMENTAL INVESTIGATION OF SYSTEM (*a*)

The mean frequency of the signals in the short-distance investigation was 1·45 Mc. ($\lambda = 207$ metres). The greater part of the work was carried out with artificial fading produced by Appleton–Barnett frequency-changes,‡ but a number of check records were obtained with natural fading. The receiving station was at Liverpool (New South Wales), distant 25 km. from the transmitter at the University of Sydney. By using the frequency-change technique it was possible to measure simultaneously the amplitude of the fading and the path-difference between ground and sky rays and thus to check the formula relating the control frequency with D'. In addition, it will be realized that a considerable saving in time was effected since it was not necessary to wait for naturally-occurring changes in the path of the sky ray.

---

* See E. V. Appleton: *Proceedings of the Physical Society*, 1928, vol. 41, p. 43, for a discussion of optical and equivalent paths in an ionized medium.

* For values of f_r close to the critical penetration frequency of an ionospheric region there will, of course, be rapid variations of f_q with changes in f_r. In practice, however, no confusion arises and it is sufficient to specify one value of f_q for waves which are reflected from the E region and another for those from the F region.

† The authors are indebted to Dr. D. F. Martyn for pointing this out.

‡ *Proceedings of the Royal Society*, A, 1925, vol. 109, p. 621.

The transmitter details need not be enumerated here beyond saying that the master oscillator was fitted with automatic frequency-change apparatus by means of which the frequency of the carrier could be varied continuously through a small range of the order 10 kc. A complete cycle of two frequency-changes took place in 6 sec.* In system (*a*), modulation was imposed in the last amplifying stage using the Heising principle, and the depth of modulation was adjusted to about 95 per cent with the help of subsidiary cathode-ray-tube apparatus.

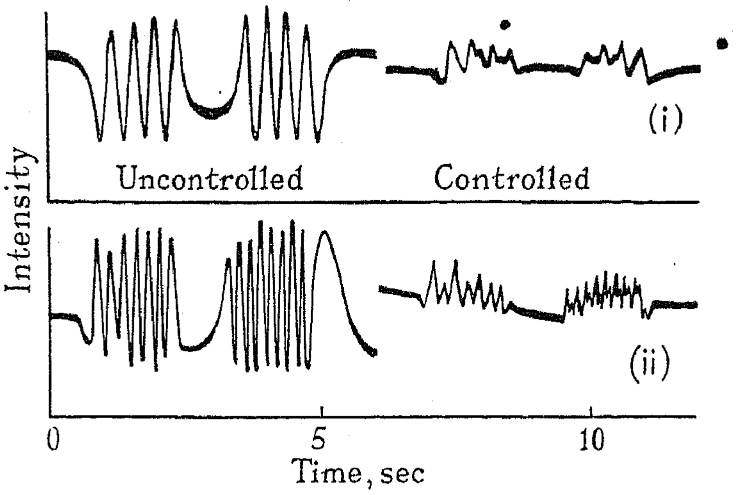


Fig. 1.—Dependence of control frequency on path-difference between ground and sky rays, system (*a*). Artificial fading produced by Appleton–Barnett frequency-changes.

(i) E region: 4·3 fringes corresponding to $D' = 215$ km., for which the control frequency was 800 cycles. The fading was reduced from about 60 per cent to 20 per cent.
(ii) F region: 7·8 fringes corresponding to $D' = 390$ km., for which the control frequency was 300 cycles.

The receiver was a 2-stage tuned radio-frequency amplifier with means for obtaining flat tuning over the 20-kc. range covered by the transmissions, and was followed by a balanced square-law detector.† For some later work a second detector was added to measure the intensity of the audio-frequency components in the anode current of the first detector. Photographic registration was employed throughout the investigation, with a Cambridge Einthoven galvanometer.

Fig. 1 shows some typical results obtained with system (*a*). Record (i) is for the period when sky rays were being reflected from the E region, and record (ii) from the F region. The uncontrolled fading was in both cases about 60 per cent [see expressions (14) and (16)], and this was reduced to about 20 per cent by the addition of control modulation at a frequency of 800 cycles in the first case and 300 cycles in the second case. No attempts were made, at this stage, to find with great accuracy the modulation frequency which gave the best control, but it will be seen that roughly it was inversely proportional to the path-difference between ground and sky rays, in accordance with the theory. It is of interest to notice

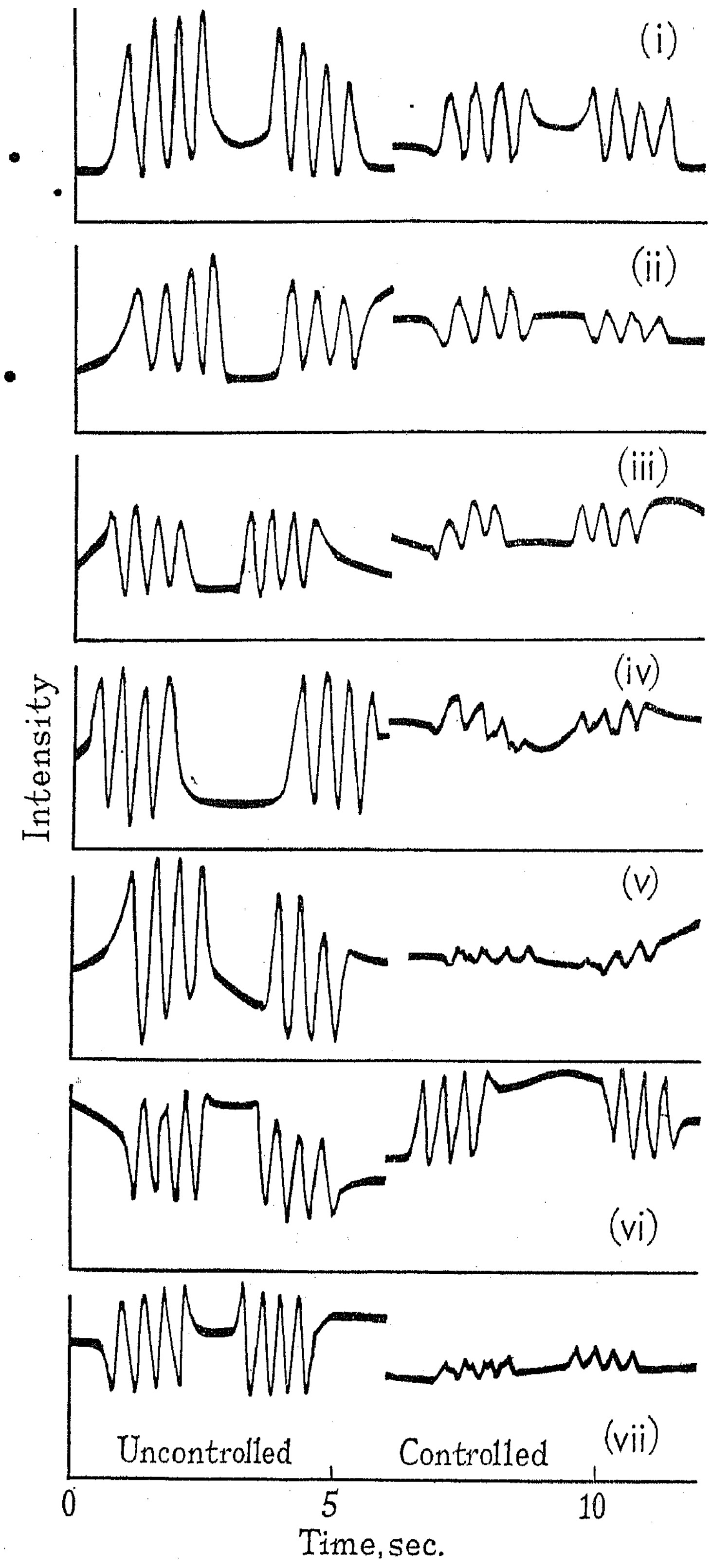


Fig. 2.—Investigation of correct modulation frequency for optimum fading control in system (*a*) and for E-region reflections.

Record	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)
Modulation frequency ..	250	400	600	800	1 200	1 800	2 500
Uncontrolled fading (per cent)	58	44	50	57	62	44	35
Controlled fading (per cent)	38	22	16	14	14	28	10

The optimum frequency was calculated to be 910 cycles for an E-region height of 95 km.

---

* When the path of the sky ray is varying rapidly owing to changing conditions in the ionosphere there will be a difference in the number of fringes produced by increasing and decreasing frequency-changes (see E. V. APPLETON: *Proceedings of the Physical Society*, 1930, vol. 42, p. 321). Hence, in the reproductions of photographic records in this paper, the authors have usually included a complete cycle of two frequency-changes, and taken the average, for the purpose of calculating D'.

† E. V. APPLETON and A. L. GREEN: *Proceedings of the Royal Society*, A, 1930, vol. 128, p. 159.

that one of the effects of the control is to emphasize the presence of subsidiary sky rays, this effect being most noticeable in record (ii).

Fig. 2 is a summary of a more detailed investigation of the frequency of modulation required for optimum fading control. All of the records were obtained between 3.30 p.m. and 5.30 p.m. (E.S.T.) on the 17th July, 1934, during a period when the height of the E region varied from 95 to 107 km. In all cases the procedure adopted was to record a series of frequency-change signals from an unmodulated carrier, followed by modulated signals.

In record (i), the modulation frequency was 250 cycles and the amount of control was small, the fading being reduced from 60 to 40 per cent. Thereafter, in records (ii), (iii), (iv), and (v), the frequency of modulation was respectively 400, 600, 800, and 1 200 cycles, and the degree of control reached a broad maximum in (iv) and (v). In record (vi), when the modulation was 1 800 cycles, the control became weak, but, with a further increase in frequency to 2 500 cycles in record (vii), a second region of good control was reached.

Owing to variations in the ionospheric conditions it was not possible to determine the optimum control frequency with very great accuracy, but it is apparent from the records that it was approximately 1 000 cycles. For comparison, the theory given above requires an optimum-frequency of 910 cycles to correspond with an E-region height of 95 km., this height being close to that observed during the tests (iv) and (v). Records (vi) and (vii) were therefore taken when the modulation frequency was respectively twice and three times the fundamental control frequency, so that we have a verification of the prediction that the odd harmonics of the control frequency are also effective in reducing fading.

The degree of control was actually somewhat better than could have been expected from the theory. The greatest reduction in fading should have been to $\frac{1}{3}$, but in records (iv) and (v) the ratio was closer to $\frac{1}{4}$. In view of the admitted difficulties of obtaining true comparisons of the modulated and unmodulated signals under strictly comparable ionospheric conditions, however, it is not thought that the small difference between theory and experiment is of significance.

The conclusions to be drawn from the investigation of system (*a*) are:—

(i) The conditions for optimum fading control are as given by the theory, i.e. 100 per cent modulation of the carrier at a frequency which satisfies the relation $\cos \chi = -1$.

(ii) The control frequencies appropriate to short-distance propagation are approximately 850 and 350 cycles respectively for normally-occurring ionospheric heights of about 100 and 220 km. The control frequency is sensibly independent of the mean frequency of the wave.

(iii) The odd harmonics of the modulation frequencies are also available for the purpose of reducing fading.

(iv) The adjustment of the control frequency is not very critical and, conversely, normally-occurring minor variations in the ionosphere do not affect appreciably the degree of control.

(v) It is not possible to obtain complete control of fading with system (*a*), the optimum to be expected being a reduction of the fading fluctuations to one-third of normal.

(4) THEORY OF SYSTEM (*b*)

There are two properties of the system (*a*) type of modulation which are, in practice, undesirable. The first of these is the necessity to maintain very deep modulation, and the second that absolute control of the fading cannot be achieved even when the adjustments are correctly made. Both of these disadvantages can be avoided by suppressing the carrier at the transmitter. In suppressed-carrier technique only the modulation side-bands are emitted and the signal at the receiver due to the ground wave is, following (1),

$$e_g = \tfrac{1}{2}\epsilon_0\left[\sin(\omega_r + \omega_q)t + \sin(\omega_r - \omega_q)t\right] \quad . \quad (18)$$

$$\equiv \epsilon_0 \cos \omega_q t \sin \omega_r t \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (19)$$

Similarly, by analogy with (8), the sky-ray signal is

$$e_s = 2\epsilon_s \cos(\omega_q t + \chi) \sin(\omega_r t + \theta) \quad . \quad . \quad (20)$$

so that, after square-law detection, the d.c. components are proportional to

$$\epsilon_0^2 + 4\epsilon_s^2 + 4\epsilon_0\epsilon_s \cos\chi \cos\theta \quad . \quad . \quad . \quad (21)$$

which is to be compared with (10) for system (*a*). As before, consideration of the audio-frequency components will be deferred. The only conditions for controlling fading in system (*b*) are obviously such that the equation

$$\cos\chi = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad (22)$$

is satisfied. The depth of modulation at the transmitter is no longer a criterion of control, and its amount is only of importance in determining the excitation of the amplifying stage which follows the suppressing unit.

Expression (22) may also be written in the form

$$\frac{\omega_q}{2\pi} = \frac{(2n+1)}{4} \cdot \frac{c}{D'} \quad . \quad . \quad . \quad . \quad (23)$$

to be compared with (12) for system (*a*). The factor 2 which differentiates (23) from (12) expresses the fact that, in a suppressed-carrier transmitting system, the frequency separation of the two emitted waves is double that of either side-band from the carrier in system (*a*). Hence, in what follows it will be understood why the control frequency for system (*b*) is one-half of that for system (*a*) for the same ionospheric conditions.

The amplitude of the fading fluctuations in system (*b*) reception is, in general,

$$A = \frac{2a\cos\chi}{1 + a^2} \quad . \quad . \quad . \quad . \quad . \quad (24)$$

When the modulation frequency is such that $\cos\chi = 1$, the fading is unaffected by the modulation, whereas, when $\cos\chi = 0$, the phase fading should be completely controlled. There will, however, remain some fluctuations in the signal caused by variations in the intensity of the sky ray, but it is clear that the signal can never fall below that due to the ground ray alone.

(5) EXPERIMENTAL INVESTIGATION OF SYSTEM (*b*)

In the main, the details of these experiments were very similar to those described for system (*a*), since it was thought desirable to repeat the whole of the previous work in order to obtain a comparison of the two systems.

As before, artificial fading was produced by wobbling the frequency of the master oscillator. In system (*b*), however, the carrier was next passed to the suppressing unit, the relevant details of which are shown in Fig. 3. From the diagram it will be seen that the carrier is in phase at the grids of the two tubes, whereas the modulation is applied in push-pull. The anode circuit common to the tubes presents negligible impedance to audio frequencies and it balances the effects of the carrier, so that the resultant output consists only of the two side-bands.

Fig. 4 shows a summary of the results obtained with artificial fading and system (*b*). Records (i), (ii), (iii), and (iv), were attempts to adjust the modulation frequency respectively to the fundamental frequency and to its 2nd, 3rd, and 4th harmonics. Records (v), (vi), and (vii), are for the 9th, 10th, and 11th harmonics of the control.

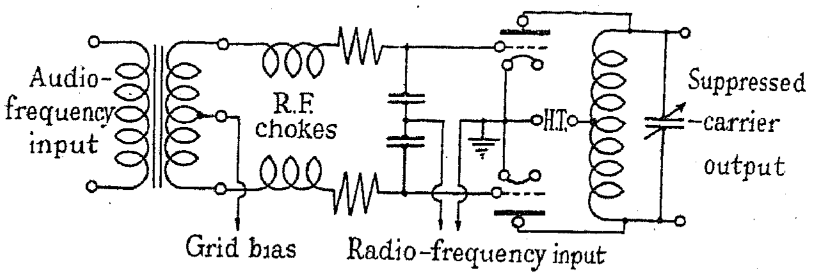


Fig. 3.—Carrier-suppression unit. The modulation is applied to the tubes in push-pull, but the radio-frequency carrier is in phase at the two grids. The anode circuit presents negligible impedance to the audio frequencies and the carrier is balanced out, so that the output consists only of the two side-bands.

Owing to changes in the ionosphere taking place during the period of the observations, it proved to be difficult to get strictly comparable conditions for the successive experiments. For example, the measured E-region heights in cases (v), (vi), and (vii), were respectively 111, 106, and 108 km., and the corresponding calculated fundamental control frequencies 380, 400, and 390 cycles. This fact will serve to explain why the modulations actually used—3 400, 4 000, and 4 200 cycles—did not differ by a constant amount in frequency although they were appropriate to the ionospheric conditions in force at the moment that each record was taken.

Record (i) in Fig. 4, showing a reduction in the uncontrolled fading from 60 per cent to 4 per cent by the addition of control modulation at a frequency of 380 cycles, should be compared with the corresponding system (*a*) records in Fig. 2, in which case the greatest degree of control was from 62 to 14 per cent.

Records (ii) and (iv), for the 2nd and 4th harmonics, show very little reduction in fading, the uncontrolled being about 80 per cent and the controlled about 70 per cent.

Record (iii) proved to be rather a poor attempt at adjustment to the 3rd harmonic owing to a sudden drop in the E-region height from 127 to 120 km. However, the ratio of the modulation frequency actually used to the true fundamental frequency was 2·7, and this is sufficiently close to the 3rd harmonic to show the expected control of fading, from 78 to 20 per cent.

Records (v), (vi), and (vii), are of unusual interest in that the modulation frequency was so high that the audio-frequency components manufactured in the detector were nearly supersonic, e.g. in the last case 8 400 cycles. The possibility of using the high harmonics in the control of telephonic transmissions has been mentioned before. The reduction of fading in record (vii) was from 60 to 9 per cent, but it must be admitted that a very small

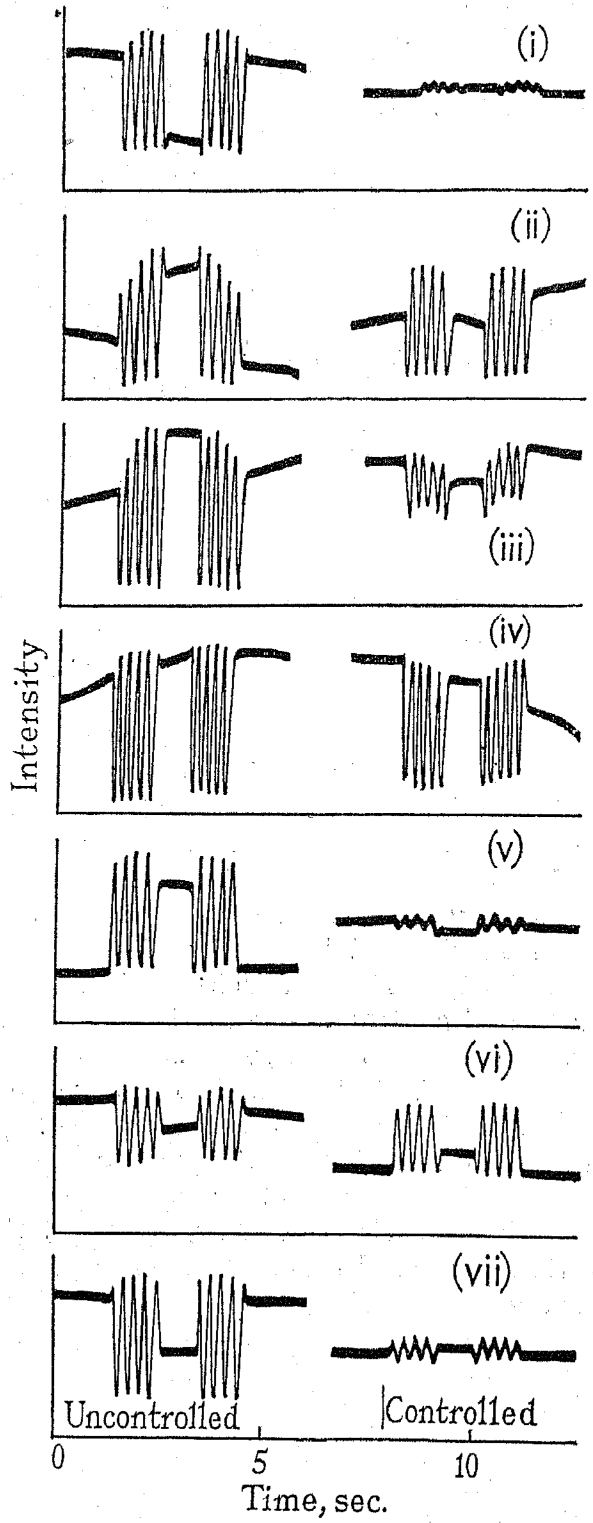


Fig. 4.—Variation of degree of fading control with frequency of modulation in system (*b*).

Record	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)
Modulation frequency ..	380	700	950	1 200	3 400	4 000	4 200
Uncontrolled fading (per cent)	58	78	78	85	52	39	59
Controlled fading (per cent)	4	68	20	72	6	32	9

The fundamental control frequency was calculated to be 328–400 cycles for the range of E-region heights (106–127 km.) observed during these tests.

ionospheric disturbance would have markedly affected the degree of control.

Fig. 5 is a summary of the records of controlled natural fading, (i) and (ii) for the E region, (iii) and (iv) for the F region; the control frequencies were respectively 380 and 160 cycles. In the four records the uncontrolled fading was always severe, the greatest fluctuations being respectively 78, 95, 95, and 92 per cent. The corresponding controlled records had fading fluctuations of 16, 31, 47, and 36 per cent. It is by no means certain that the residual fading was due to phase interference, however, and it seems likely that the greater part of it was caused by intensity changes in the sky ray. This conclusion is strongly supported by an examination of earlier records taken on the same afternoon from which the intensity of the ground ray can be estimated. With the help of these earlier records it is possible to infer that the controlled signal did not fall below the ground-ray level, and hence it is probable that the residual fading was due to variations of $4\epsilon_s^2$.

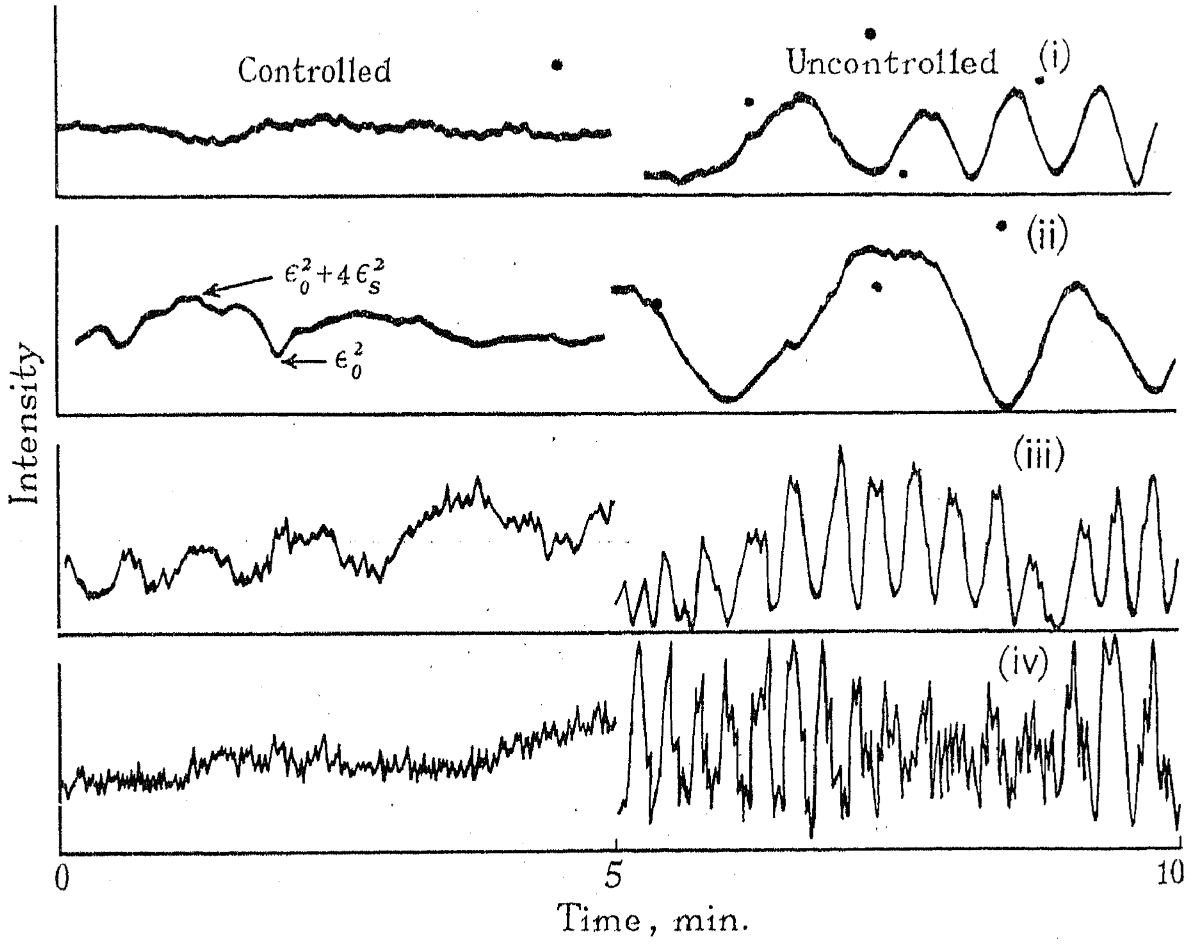


Fig. 5.—Control of natural fading with system (*b*).

Records (i) and (ii).—Typical E-region results, control frequency 380 cycles.
Records (iii) and (iv).—Typical F-region results, control frequency 160 cycles.

The conclusions to be drawn from the investigation of system (*b*) are:—

(i) The condition for optimum fading control is, as given by the theory, $\cos \chi = 0$.

(ii) The modulation frequencies appropriate to short-distance propagation are half those specified for system (*a*).

(iii) The odd harmonics of the control frequency, at least as high as the 11th, are effective in reducing fading.

(iv) The adjustment of the fundamental control frequency for optimum reduction of fading is not critical, but the process becomes increasingly difficult with higher harmonics.

(v) Theoretically it is possible to obtain control of phase fading to any desired degree. The best experimental result was a reduction of fading from 60 per cent (uncontrolled) to 4 per cent.

(6) FADING OF AUDIO-FREQUENCY COMPONENTS IN SYSTEM (*a*)

The method of reception used throughout the tests has been a galvanometric one, and it has been tacitly assumed that the application of the two systems of fading control to circuits carrying messages would be on similar lines—for example, by inserting a d.c. relay into the anode circuit of the detector. It is, however, obvious that there must also be audio-frequency components of the signal in the output of the detector, and it is a matter for investigation whether these sounds are controlled as to fading. Listening to the signal certainly gives no indication that they are controlled and, in fact, further experimental work has led to the conclusion that it is the d.c. component alone which is useful for carrying messages.

The signal at the grid of the square-law detector is, according to (9),

$$e = \epsilon_0(1 + Q \cos \omega_q t) \sin \omega_r t + 2\epsilon_s[1 + Q \cos (\omega_q t + \chi)] \sin (\omega_r t + \theta)$$

After detection, the audio-frequency components in the anode circuit are proportional to

$$\begin{aligned}&\epsilon_0^2(4Q\cos\omega_q t + Q^2\cos 2\omega_q t)\\ &\quad + 4\epsilon_s^2\left[4Q\cos(\omega_q t+\chi) + Q^2\cos 2(\omega_q t+\chi)\right]\\ &\quad + 4\epsilon_0\epsilon_s\cos\theta\left[4Q\cos\frac{\chi}{2}\cos\left(\omega_q t+\frac{\chi}{2}\right) + Q^2\cos(2\omega_q t+\chi)\right] \quad . \quad (25)\end{aligned}$$

there being notes of angular frequency ω_q and $2\omega_q$. The intensity of these audio-frequency components was experimentally measured by inserting a transformer into the detector anode circuit and connecting an additional detector to the secondary winding. The galvanometer was then transferred to the anode circuit of the 2nd detector.

Using the abbreviation $a = 2\epsilon_s/\epsilon_0$, the galvanometer deflection is proportional to

$$\begin{aligned}&16Q^2\epsilon_0^4[(1-a^2)^2 + 2a(a+\cos\theta)(1+a\cos\theta)\\ &\quad(1+\cos\chi)] + Q^4\epsilon_0^4[(1-a^2)^2 + 4a(1-a)^2\cos\theta\cos\chi\\ &\qquad + 4a^2(\cos\theta+\cos\chi)^2] \quad . \quad (26)\end{aligned}$$

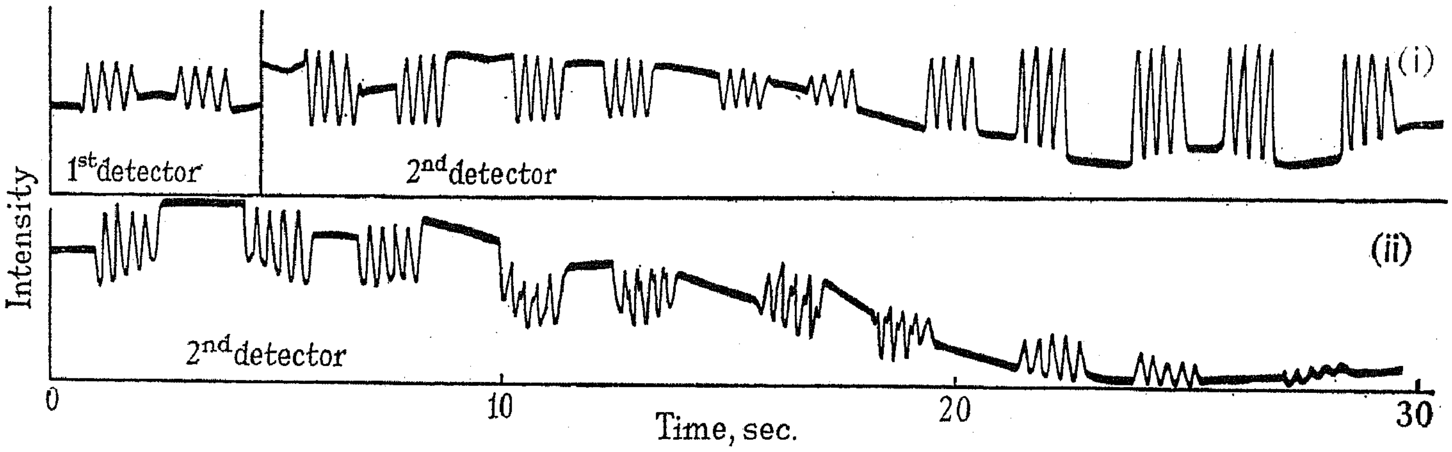


Fig. 6.—Fading of the audio-frequency components in system (*a*).

Record (i).—Comparison of fading of d.c. component of detector output with fading of audio-frequency components as measured by a second detector.
Record (ii).—Variation of mean intensity of audio-frequency components with a change in the intensity of the sky ray.

Usually it will be valid to neglect the term containing Q^4, which has been produced by the 2nd-harmonic distortion of the 1st detector. Fading fluctuations in the audio-frequency components are then determined by the maximum and minimum values of expression (26) relative to variations of θ, and we have

$$\left.\begin{aligned}I^2_{max.} &\propto (1-a^2)^2 + 2a(1+a)^2(1+\cos\chi)\\ I^2_{min.} &\propto (1-a^2)^2 - 2a(1-a)^2(1+\cos\chi)\end{aligned}\right\} \quad . \quad (27)$$

so that,

$$A_2 \equiv \frac{I^2_{max.} - I^2_{min.}}{I^2_{max.} + I^2_{min.}} = \frac{2a(1+a^2)(1+\cos\chi)}{(1-a^2)^2 + 4a^2(1+\cos\chi)} \quad (28)$$

On putting in the condition for fading control of the d.c. component, $\cos\chi = -1$, it would appear that $A_2 = 0$, independently of the depth of modulation at the transmitter. Hence, it would seem that a greater degree of fading control could be achieved in the case of system (*a*) by using the audio-frequency components in preference to the d.c. change in detector output. This result is in apparent contradiction with our experimental work, but the anomaly is removed by closer consideration of (28).

It will be remembered that it is always a matter of some difficulty to adjust the modulation frequency exactly to the ionospheric conditions prevailing at any moment. Consequently, the important quantity to be considered is the degree of fading control which it is possible to obtain when the modulation frequency differs from the true control frequency by some small amount. In that case it may be shown, by making the substitution $a \rightarrow 1$ in (28), that the fading tends to 100 per cent under the usual experimental conditions of approximate equality of ground- and sky-ray intensities. It is therefore easy to see why, in practice, the adjustment for control of the audio-frequency components was never exactly realized.

There is an even more serious objection, however, to the use of the audio-frequency components. From (28) it follows that the mean intensity of these components is

$$\frac{I^2_{max.} + I^2_{min.}}{2} = (1-a^2)^2 + 4a^2(1+\cos\chi) \quad . \quad (29)$$

and this tends to zero when $\cos\chi \rightarrow -1$ and $a \rightarrow 1$.

Hence this study of the audio-frequency components in system (*a*) leads to the following predictions:—

(i) Unless the fading-control condition is very exactly fulfilled, the fading is always considerable under the normally occurring experimental condition of approximate equality of ground- and sky-ray intensities.

(ii) When the fading control is approximately adjusted and when the ground- and sky-ray intensities are nearly equal, the mean intensity of the audio-frequency components tends to zero.

These two points are illustrated in Fig. 6. In record (i) there is a comparison of the residual fading of the d.c. components as measured by the galvanometer in the 1st detector, with the residual fading of the audio-frequency components as estimated by the 2nd detector. Although only one complete cycle of frequency-changes is shown for the 1st detector, it may be stated that it is a fair sample of the remainder of the record from which it was taken and that the residual fading was always about

25 per cent. On the other hand, the amount of the residual fading of the audio-frequency components varied very rapidly. In the 30 seconds occupied by the part of the record reproduced, the fading varied from 15 to 60 per cent, this being typical of other results obtained with the audio-frequency components and confirmatory of prediction (1) above.

In Fig. 6 (ii) there is shown a very good example of a sudden increase in intensity of the sky ray producing a marked drop in the mean intensity of the audio-frequency components. At the beginning of the record the mean intensity was high and the amount of fading about 20 per cent, whereas only 30 seconds later the mean intensity had fallen to one-eighth of its former value and the fading had increased to 80 per cent.

Both records of Fig. 6 were taken at a time when the sky ray was being returned from the E region, for which conditions the modulation frequency was 800 cycles.

The conclusions to be derived from this section are therefore in accordance with predictions (i) and (ii) above.

(7) FADING OF AUDIO-FREQUENCY COMPONENTS IN SYSTEM (*b*)

From (19) and (20), the signal at the grid of the detector is proportional to

$$\epsilon_0 \cos \omega_q t \sin \omega_r t + 2\epsilon_s \cos (\omega_q t + \chi) \sin (\omega_r t + \theta) \quad . \quad (30)$$

After detection, the audio-frequency components in the output circuit are

$$\epsilon_0^2 \cos 2\omega_q t + 4\epsilon_s^2 \cos 2(\omega_q t + \chi) + 4\epsilon_0\epsilon_s \cos \theta \cos (2\omega_q t + \chi) \quad . \quad (31)$$

which consist entirely of notes of angular frequency $2\omega_q$. After adding the 2nd detector and transferring the galvanometer, the signal is proportional to

$$\epsilon_0^4\left\{1 + a^4 + 2a^2 \cos 2\theta + 4a \cos \chi\left[a \cos \chi + (1 + a^2) \cos \theta\right]\right\} \quad . \quad (32)$$

In system (*b*), the condition for fading control of the d.c. components is $\cos \chi = 0$, so that, with this satisfied, the intensity of the audio-frequency components is proportional to

$$1 + a^4 + 2a^2 \cos 2\theta \quad . \quad . \quad . \quad . \quad (33)$$

and the residual fading is determined by

$$A_2 = \frac{2a^2}{1 + a^4} \quad . \quad . \quad . \quad . \quad . \quad (34)$$

From (33) and (34) we may predict that:—

(i) Owing to the effect of the term containing $\cos 2\theta$, the rapidity of fading is just double that of an unmodulated wave. This happens only when the condition for fading control of the d.c. component is exactly satisfied.

(ii) The fading of the audio-frequency components is completely uncontrolled.

These conclusions have been experimentally verified, and a summary of the results obtained is given in Fig. 7. In record (i) the residual fading of the d.c. component is shown on the right-hand side of the diagram and is about 4 per cent. The fading of the audio-frequency components varied from 65 per cent at the beginning of the record to about 40 per cent at the end and, in addition, there was a marked drop in the mean signal during the same period. From expression (33) it is seen that the mean intensity of the audio-frequency components is proportional to $(1 + a^4)$, so that the decrease in mean intensity shown in record (*a*) is to be attributed to a decrease in the intensity of the sky ray.

Records (ii), (iii), (iv), and (v), show the gradual development of spurious secondary fringes, due to the term in (33) which contains $\cos 2\theta$. In every case the corresponding 1st-detector signals are shown on the right-hand side of each record. In them there are no signs of secondary fringes, and therefore the possibility can be ruled out of a doubly-reflected sky ray being present at the time and producing true subsidiary fringes.

The graph shows the variation in equivalent height of the E region during the period of the tests. At the time that record (i) was obtained the equivalent height was 97 km., rising to 125 km. for record (vi). The steady increase in height, which is known to occur frequently at this time of the day, was utilized for the purpose of adjusting D' exactly to the control frequency. Throughout the afternoon the modulation remained at 400 cycles and, when the height reached 106 km. at 5.10 p.m. and record (v) was obtained, the primary fading was completely controlled and only the spurious subsidiary fringes remained. Later in the afternoon, when record (vi) was taken, the ionospheric conditions had become sufficiently out of step with the control frequency for the primary fading again to have taken charge.

One other point should be stressed. Throughout the development of this cycle of changes in the fading of the audio-frequency components, the appearance of the 1st-detector records remained substantially unchanged. In no case did the fading of the d.c. component exceed 5 per cent, although the value of D' varied considerably during the course of the afternoon. This shows that the adjustment of the control frequency is by no means critical in the case of the d.c. component, but extremely so for the audio-frequency components.

The conclusions to be derived from this section are therefore in accord with predictions (i) and (ii) above.

(8) AN APPLICATION TO IONOSPHERIC RESEARCH

Fig. 8 shows a phenomenon, which was mentioned earlier in this paper, wherein it sometimes happens that the suppression of the main sky-ray discloses the presence of an unsuspected subsidiary ray.

Now it is well known that accurate measurements, by the Appleton–Barnett frequency-change method, of polarization and lateral deviation of the main sky-ray are impossible if the subsidiary rays are strong.* When the subsidiary ray exceeds a certain threshold intensity its presence may be detected by the appearance of "kinks" on the main fringes† and usually it is necessary to reject all such records when precise measurements are required. However, fading-control technique now provides an additional test of the purity of the main fringes which may be used even when the subsidiary ray is below the threshold value.

---

* See J. A. Ratcliffe and J. L. Pawsey: *Proceedings of the Cambridge Philosophical Society*, 1933, vol. 29, p. 301; also D. F. Martyn and A. L. Green: *Proceedings of the Royal Society*, A, 1935, vol. 148, p. 104.

† E. V. Appleton: *Proceedings of the Royal Society*, A, 1930, vol. 126, p. 542.

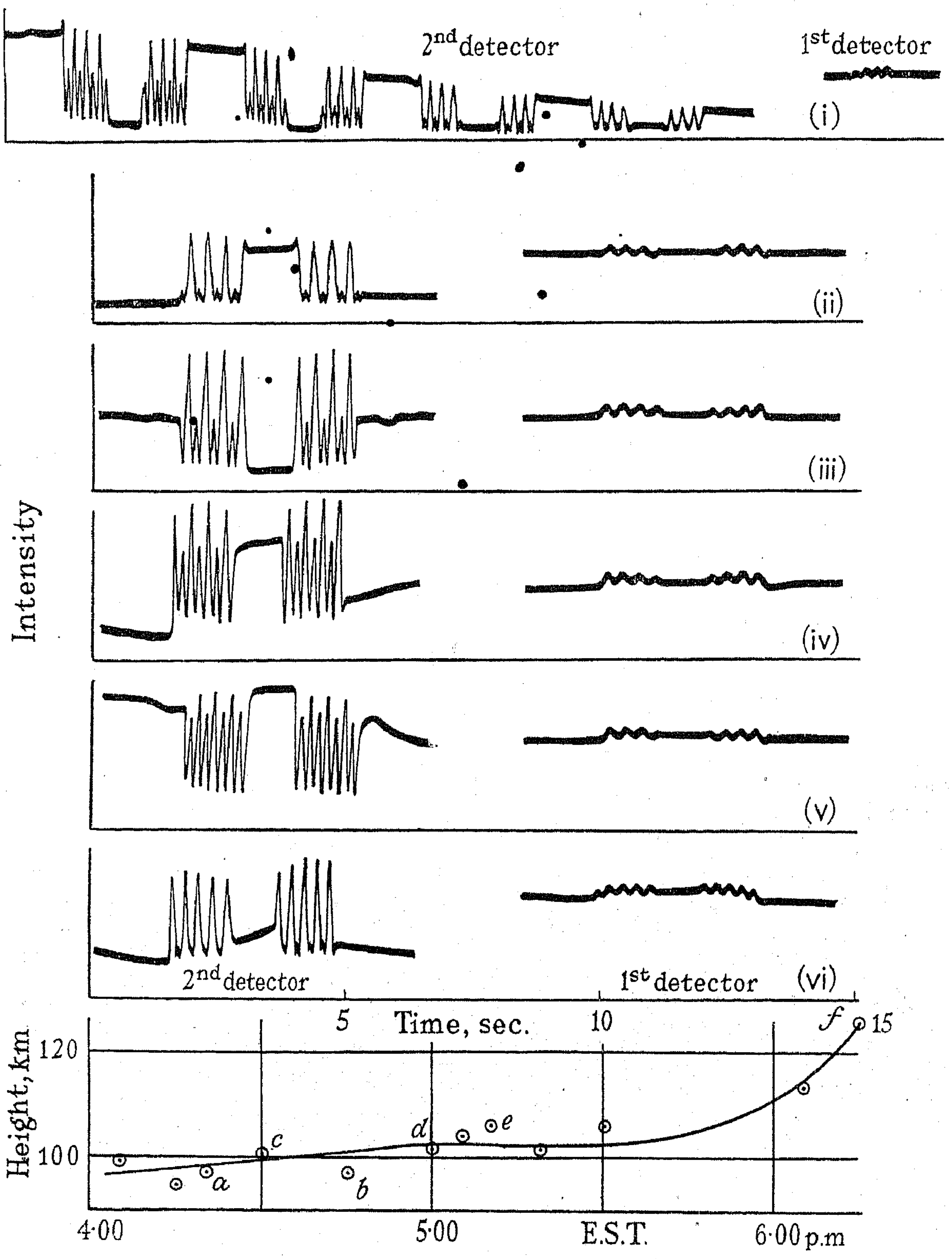


Fig. 7.—Fading of the audio-frequency components in system (*b*).

Record (i).—Comparison of residual fading of audio-frequency components, 2nd detector, with controlled fading of d.c. component in 1st detector. Records (ii), (iii), (iv), (v), (vi).—Development of subsidiary fading with precise adjustment of fading control.
The graph shows the variation of E-region height during period of tests, the points marked *a–f* corresponding to records (i)–(vi) above.

In Fig. 8 the amount of the frequency-change is only 4 kc., so that the 2·6 fringes in record (i) indicate an E-region height of 110 km. After the main sky-ray has been suppressed, by using a control frequency of 400 cycles, there appear on the record about 6 fringes for an F-region height of 237 km. In record (ii), the presence of the F sky-ray is also exhibited in the subsidiary fringes appearing on the main fringes; and, after suppression, the F fringes proper are seen to have increased in amplitude. In record (iii) the jump has occurred, and both controlled and uncontrolled records show the F-region fringes.

The theory of this effect is as follows. Using the subscripts 1 and 2 for the two sky rays, the signal at the receiver is, in system (*b*) transmissions,

$$\epsilon_0 \cos \omega_q t \sin \omega_r t + 2\epsilon_1 \cos (\omega_q t + \chi_1) \sin (\omega_r t + \theta_1) + 2\epsilon_2 \cos (\omega_q t + \chi_2) \sin (\omega_r t + \theta_2) \quad . \quad (35)$$

where

$$\left.\begin{aligned} \theta_{1,2} &= -\frac{\omega_r}{c} D_{1,2} \\ \chi_{1,2} &= -\frac{\omega_q}{c} D'_{1,2} \end{aligned}\right\} \quad . \quad (36)$$

After square-law detection, the d.c. component in the anode circuit of the detector is proportional to

$$\epsilon_0^2+4\epsilon_1^2+4\epsilon_2^2+4\epsilon_0\epsilon_1\cos\theta_1\cos\chi_1+4\epsilon_0\epsilon_2\cos\theta_2\cos\chi_2 \\ +8\epsilon_1\epsilon_2\cos(\theta_2-\theta_1)\cos(\chi_2-\chi_1) \quad . \quad (37)$$

In the experimental case considered above, the path of the F sky-ray was approximately double that of the E-region ray, i.e. $D_2 \simeq 2D_1$. In addition, $\chi_2 \simeq 2\chi_1$ and the condition for control of the E ray is $\cos\chi_1 = 0$, so that the signal remaining is

$$\epsilon_0^2 + 4\epsilon_1^2 + 4\epsilon_2^2 - 4\epsilon_0\epsilon_2\cos\theta_2 \quad . \quad . \quad (38)$$

It follows that the fringes corresponding to the main ray have been suppressed, but there is an increase in the mean intensity of the signal due to the term $4\epsilon_1^2$. In practice, therefore, estimates of the intensity of the subsidiary ray will be in error unless this effect is allowed for.

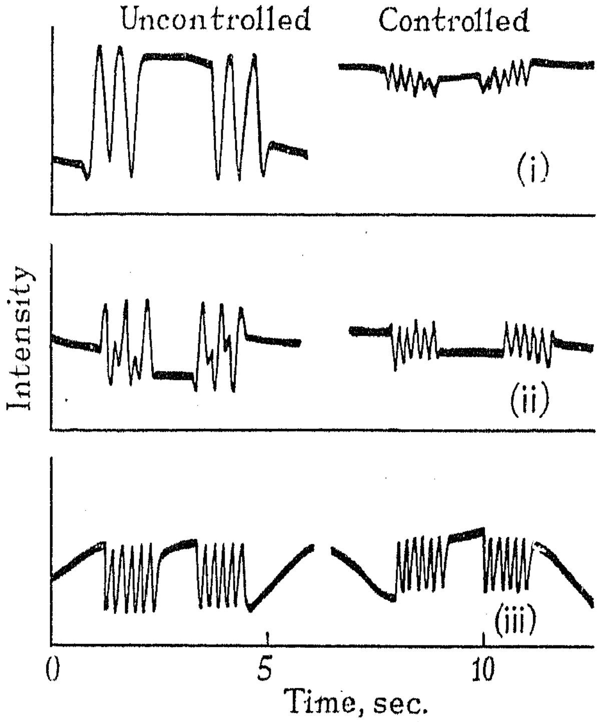


Fig. 8.—Suppression of sky ray from E region in favour of one from F region. In record (iii), the jump to the F region had occurred, and both the controlled and the uncontrolled transmission gave the same result.

For Fig. 8(i), where the main fringes are smooth and the only indication of the presence of the subsidiary sky-ray is a slight rounding-off at the apices of the main fringes, it can be calculated that $2\epsilon_1/\epsilon_0 = 0\cdot36$. From the suppressed record in Fig. 8(i) it may similarly be calculated that $2\epsilon_2/\epsilon_0 = 0\cdot04$. Hence it follows that $\epsilon_1/\epsilon_2 = 9$ for a case in which no "kinks" appeared on the main fringes. In record (ii), where the subsidiary fringes are clearly discernible on the uncontrolled signals, $2\epsilon_1/\epsilon_0 = 0\cdot29$ and, from the controlled signals, $2\epsilon_2/\epsilon_0 = 0\cdot11$. Hence in this case $\epsilon_1/\epsilon_2 = 2\cdot6$, and the appearance of kinks on the main fringes is associated with a subsidiary ray whose intensity is somewhat greater than one-third of the main ray.

In record (iii), where the E sky-ray has disappeared, the ratio of controlled to uncontrolled F-region signals is about 0·8, thus verifying that the effect of the control on the F ray is small.

Another way of looking at this effect is to remember that, when $D_2 \simeq 2D_1$, the control frequency suitable for the E ray is equal to the 2nd harmonic of that which would control the F ray. The experimental results of previous sections then show immediately why it is possible to suppress the one ray without markedly affecting the other. Conversely, it follows that it is not possible to suppress the subsidiary ray without reducing the amplitude of the main fringes.

(9) APPLICATION TO DIRECTION-FINDING

It is well known that a simple loop direction-finder suffers from night effect, the manifestations of which are blurred minima accompanied by large errors in the apparent bearing. These errors are greatest when the received signals due to ground and sky rays are approximately equal, and in certain cases it has been found[*] that the apparent bearing can make complete rotations of 360°. It is therefore of some considerable interest that the theory of system (*b*) predicts the elimination of wandering minima.

Consider, as in Fig. 9, the reception in a rotatable loop of a ground ray H_0 and an elliptically polarized sky ray having components of magnetic force H_1 and H_1' respectively perpendicular to and in the plane of propagation. The phase difference between the magnetic components is ξ and it is supposed that the polarization of the downcoming wave does not vary appreciably[†] in the range of angular frequencies $(\omega_r \pm \omega_q)$ required by system (*b*) modulation.

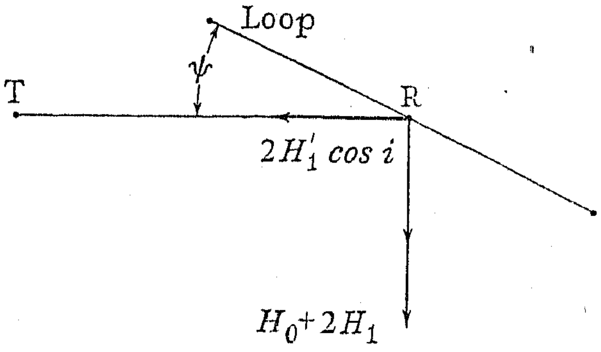


Fig. 9.—Ground plan of magnetic forces affecting a rotatable loop. The sky ray has an angle of incidence i at the ground.

When the loop is placed at an angle ψ to the direction of propagation, the signal induced into it is proportional to

$$H_0\cos\psi\cos\omega_q t\sin\omega_r t \\ +2H_1\cos\psi\cos(\omega_q t+\chi)\sin(\omega_r t+\theta) \\ +2H_1'\cos i\sin\psi\cos(\omega_q t+\chi)\sin(\omega_r t+\theta') \quad (39)$$

where i is the angle of incidence of the sky ray and $\theta' - \theta = \xi$. On using the abbreviations

$$a = 2H_1/H_0 \quad \text{and} \quad a' = (2H_1'/H_0)\cos i \quad . \quad (40)$$

and applying the condition for fading control ($\cos\chi = 0$), the d.c. component in the output of the detector is found to be proportional to

$$H_0^2\left[(1+a^2)\cos^2\psi + a'^2\sin^2\psi + aa'\cos\xi\sin 2\psi\right] \quad (41)$$

---

[*] R. L. SMITH-ROSE and R. H. BARFIELD: *Journal I.E.E.*, 1926, vol. 64, p. 831.

[†] This hypothesis is in agreement with the conclusions of Baker and Green (*Proceedings of the Institute of Radio Engineers*, 1933, vol. 21, p. 1103).

which does not contain θ. Hence, on rotating the loop until $\psi = 90°$, the minimum signal so obtained will always indicate the true bearing of the station, independently of the presence of abnormal polarization in the sky ray. In cases of severe night-effect, however, the minimum will be blurred and the accuracy of taking the bearing low.

For purposes of illustration there have been plotted in Fig. 10 the polar diagrams of reception of a rotatable loop, it being assumed that the indicating instrument is a d.c. meter placed in the anode circuit of the square-law detector. In Fig. 10(*a*) the sky ray is circularly polarized; that is, $H_1 = H_1' \cos i$ and $\xi = 90°$. The three curves are respectively for equal intensities of ground and sky rays, sky ray equal to one-half of ground ray, and ground ray alone. In Fig. 10(*b*) the sky ray is linearly polarized with $H_1 = H_1' \cos i$ and $\xi = 0°$. Three curves are plotted, as for Fig. 10(*a*).

In both cases it is apparent that severe blurring of the minimum only occurs when the intensities of the ground and sky rays approach equality. Under similar conditions, but using uncontrolled transmissions, the minimum would be both blurred and wandering. No experimental tests have yet been made of this arrangement, but it is clear that the principles underlying the proposed system are applicable equally well to a rotating loop direction-finder or to a rotating beacon.*

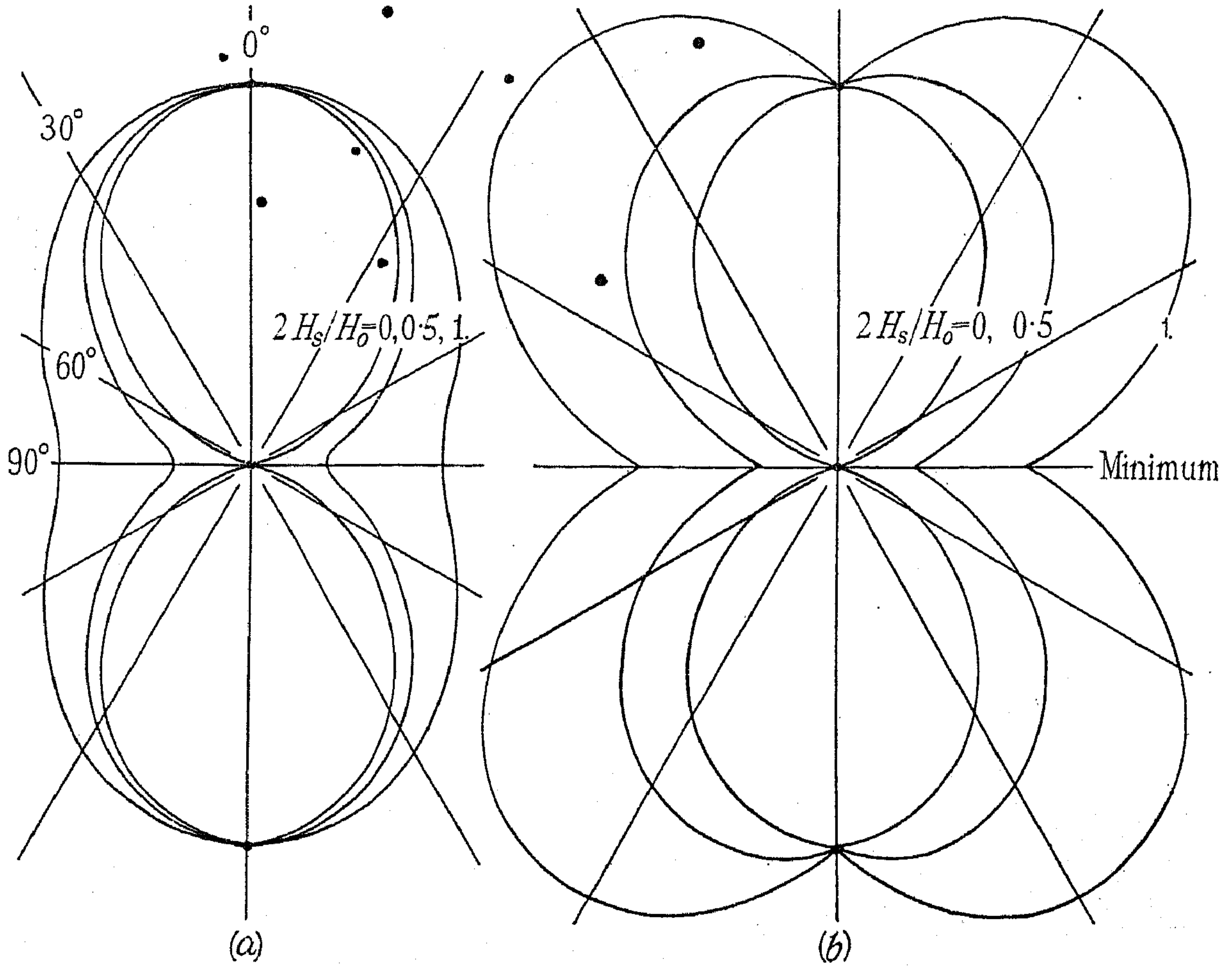


Fig. 10.—Polar diagrams of rotatable loop aerial receiving the system (*b*) controlled signals. The minimum signal always indicates the true bearing of the station, but severe "night effect" blurs the minimum.

(*a*) Circularly polarized sky ray. (*b*) Linearly polarized sky ray.

(10) APPLICATIONS TO BROADCAST TELEGRAPHY AND TELEPHONY

These two applications of the system of fading control are conveniently considered together. In the first place, it is of interest to calculate roughly the degree of control which should be obtained at various locations of the receiver when the control frequency is adjusted to be correct for one particular distance between sender and receiver.

The results for a typical case are shown in Fig. 11, for which the percentage fading has been calculated for uncontrolled and for controlled system (*b*) transmissions. The mean frequency is 300 kc. ($\lambda = 1\,000$ metres), and it is assumed that the ground ray is propagated* over country of equivalent conductivity 10^{-13} e.m.u. The intensity of the sky ray is also known,† so that the degree of fading may be calculated for any given distance from the transmitter. The worst fading occurs at a distance of 400 km., but it would be a matter for trial to decide at what particular distance the control could best be adjusted. In the case to which Fig. 11 refers, however, the control has been arbitrarily centred on 300 km. and it has been assumed that the effective height of the E region is 100 km. The corresponding control frequency for system (*b*) signals is 1 250 cycles.

The results to be expected are that the night-time fading should be negligibly small throughout the useful daylight range of the ground ray. Beyond 400 km., where the sky-ray intensity is greater than that of the ground ray, the amount of fading depends chiefly on intensity variations in the sky ray and not on phase interference. The investigation of propagation outside the range of the ground ray will, however, be dealt with in a later paper.

---

* R. L. Smith-Rose and S. R. Chapman: *Journal I.E.E.*, 1928, vol. 66, p. 256.

* T. L. Eckersley: *Proceedings of the Institute of Radio Engineers*, 1932, vol. 20, p. 1555.

† D. F. Martyn: *Proceedings of the Physical Society*, 1935, vol. 47, p. 323.

It is to be emphasized that the predicted control of fading applies only to the d.c. component in the output of the detector. In many cases it would be more convenient to read the message in telephones, so that it is a matter of some interest to investigate the possibility of imposing a second modulation on to the transmissions for the purpose of carrying intelligence. This subject is closely allied to the control of fading in telephony, which will now be discussed.

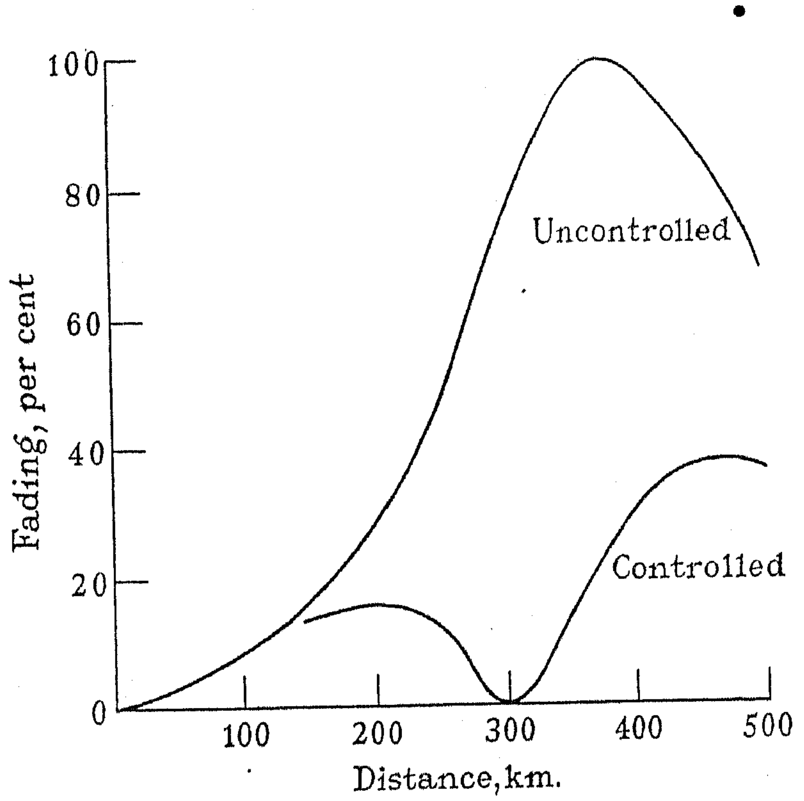


Fig. 11.—Variation of degree of control at various distances from the transmitter when the modulation frequency is adjusted to be correct for a receiver at a distance of 300 km. System (*b*), wavelength 1 000 m., control frequency 1 250 cycles.

It is evident that there are several possible modifications of the simple controlled systems by means of which telephony may be included in the transmissions. The simplest of these from the theoretical point of view is that shown diagrammatically in Fig. 12. Two carriers are emitted at angular frequencies $\omega_r \pm \omega_q$, and each is associated with a single side-band which carries the programme modulation of angular frequency ω_p. The angular frequency separation $2\omega_q$ of the carriers must therefore be somewhat greater than the highest audio frequency in the programme, e.g. greater than 5 000 cycles. It is thus necessary to select some value of ω_q which is an odd harmonic of the fundamental control frequency, e.g. the 7th harmonic when the control frequency is about 400 cycles.

However, analysis of a number of such systems discloses that:—

(i) The addition of control modulation introduces distortion into the programme, even in daylight reception.

(ii) It seems to be necessary to use a square-law detector in the receiver in the place of the now almost universal diode detector.*

(iii) The process of setting up the controlled signals at the transmitter is complicated.†

(iv) When, however, the control modulation is adjusted to suppress fading of the carrier, phase fading of the programme is simultaneously controlled.

Consequently, it is not to be anticipated that there can be an immediate application of controlled systems to high-fidelity broadcast transmissions. Nevertheless, in the case of long-distance point-to-point speech circuits which suffer from severe fading and ionospheric distortion, it might be preferable to use the control and to tolerate factors (i), (ii), and (iii) above.

The chief advantage of such a system of telephony would be in the regulation of very deep fades, at the troughs of which there is usually a noticeable distortion of the programme. The origin of this "trough distortion"‡ may be traced quite simply to the disappearance of the carrier at times when the received waves are equal in intensity but in phase opposition. Elimination of the carrier implies simultaneously the disappearance of the programme notes, since they are produced by beating the carrier with the side-bands. The distortion terms which remain are then due to beats between the two side-bands. Now it is known that fading-control systems are capable of reducing the fading of the carrier. Consequently, it is to be anticipated that the same process would have the effect of very materially reducing the amount of trough distortion.

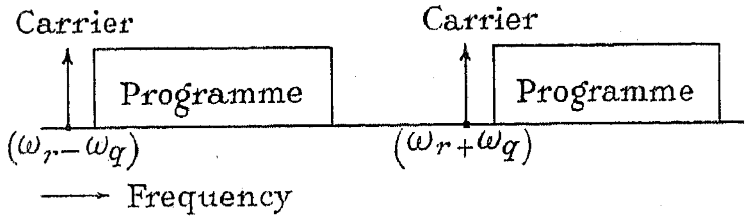


Fig. 12.—Proposed telephony system embodying two carrier + single-side-band transmissions.

Again, it must be remembered that the primary object of this investigation of the possibility of imposing two modulations on the transmissions is for the purpose of telegraphy. In the reception of these signals, factors (i) and (ii) above are of little importance. Moreover, there is one special case of the system of two single-side-bands, when $\omega_q = 3\omega_p$, for which factor (iii) also admits of an easy experimental solution. The investigation of such a double-modulation system in long-distance propagation will form the subject of a later communication.

---

* However, it is interesting to note that there has recently been a tendency towards advocating the use of asymmetrical side-band transmissions for high-quality broadcasting. See, for example, P. P. Eckersley: *Journal I.E.E.*, 1935, vol. 77, p. 517.

† A. H. Reeves: *ibid.*, 1933, vol. 73, p. 245.

‡ The authors are indebted to Mr. S. H. Witt, of the Australian Postmaster-General's Department, for some discussion of this point.

(11) CONCLUSIONS

The paper outlines an investigation of systems of fading control in which an improvement in the constancy of the received signal is produced by combining the effects of two or more signals transmitted at different frequencies. The object of such a system is to remove the deep troughs of fading under which the operation of automatic-volume-control apparatus in the receiver breaks down, owing to the signal falling below the noise-level.

The most obvious way of setting up multi-frequency transmissions is to modulate the amplitude of the carrier, thus producing two side-bands equally spaced from the carrier. In this system (*a*), however, the authors have found that it is necessary to modulate the carrier to a depth of 100 per cent, and even then the control of fading is not complete. Under optimum conditions it is possible to reduce the fading fluctuations to one-third of those experienced with unmodulated signals.

In system (*b*), in which the carrier is suppressed at the transmitter and only the side-bands are sent out, it is possible to obtain complete control of fading. In several instances fading greater than 60 per cent was easily reduced to less than 5 per cent on imposing suppressed-carrier modulation at a frequency of about 400 cycles.

With both systems it is found that the only satisfactory method of conveying intelligence is to insert into the output circuit of the detector in the receiver a device which is actuated by the change in direct current produced by the rectification of the incoming signals. In general, the audio-frequency components in the detector output are uncontrolled, so that listening to the signals in telephones is unsatisfactory.

Although the frequency of the modulation required for optimum control of fading is dependent, in short-distance propagation, on the path-difference between the ground and sky rays, yet the adjustment is not very critically affected by minor variations in the ionospheric conditions. Consequently, in broadcast telegraphy it should be possible to centre the control arbitrarily at any convenient distance from the transmitter. The zone inside which partial control is obtained then covers a wide area, and, in one special case for which detailed calculations were made, it would appear that the night-time fading could be reduced to negligible proportions throughout the useful daylight range of the ground ray.

The control frequency is sensibly independent of the mean frequency of the wave, except so far as the path of the sky ray depends on frequency.

An application of fading-control methods is suggested in connection with ionospheric research when using the Appleton–Barnett frequency-change technique. It has been discovered that suppression of the main sky-ray occasionally has the effect of disclosing the presence of an unsuspected subsidiary sky-ray. Usually it is necessary to reject all records which show signs of subsidiaries when precise measurements are required of polarization and lateral deviation of the main ray. The new technique therefore enables a test to be made of the purity of the sky ray and hence a selection of the simple experimental conditions which are required.

It is also suggested that there may be an application to direction-finding both in the transmissions from rotating beacons and in the reception by rotatable loops. The analysis predicts that such controlled systems should be free from wandering bearings during periods of night effect. In very severe conditions of approximate equality of ground- and sky-ray intensities there will, however, be a blurring of the minimum and some difficulty in making an accurate estimate of the bearing.

Theoretically it would seem to be possible to apply fading control to telephony. It has been shown that the odd harmonics of the fundamental control frequency are also available for reducing fading. Hence it might be feasible to make the control supersonic and to insert additional modulation carrying intelligence. This process, however, will introduce some distortion into the programme, so that the application of fading control to high-fidelity broadcasting is not practicable.

The whole of the investigation described in this paper has been carried out at a short distance from the sending station under conditions of approximate equality of ground- and sky-ray intensities. In a more recent investigation, to be described later, attention has been directed to the problem of imposing two modulations on to the transmissions in the case of long-distance sky-ray propagation, one modulation being used for control and the other for carrying the message.

(12) Acknowledgments

The investigation formed a part of the programme of the Radio Research Board of the Australian Commonwealth Council for Scientific and Industrial Research, with whose permission the paper is published.

The authors are indebted to Mr. A. H. Mutton, B.E., and Dr. O. O. Pulley, for help at the transmitter, and to Prof. J. P. V. Madsen, of the P. N. Russell School of Engineering of the University of Sydney, for help and advice throughout the progress of the work.

[The discussion on this paper will be found on page 633.]

CONTROL OF PHASE-FADING IN LONG-DISTANCE RADIO COMMUNICATION

By A. L. GREEN, M.Sc., Ph.D., Associate Member, and O. O. PULLEY, B.E., Ph.D.

(*Paper first received* 21*st January, and in final form* 23*rd June*, 1936; *read before the* WIRELESS SECTION 6*th January, and before the* NORTHERN IRELAND SUB-CENTRE 16*th March*, 1937.)

SUMMARY

The paper describes a continuation of fading-control experiments by methods which rely on transmissions being made at adjacent frequencies. Measurements have been made at distances of 700 and 3 300 km. from the transmitter, and it is found that phase-fading is due to interference between two main sky-rays of comparable intensity. The path-differences between these rays have been measured with the help of the Appleton–Barnett frequency-change technique and the corresponding control modulations applied.

The most satisfactory type of controlled signal is obtained by imposing two modulations having frequencies in a 3 : 1 ratio and by suppressing the carrier. The optimum control frequencies were found to be 200 and 600 cycles when the distance between sender and receiver was 700 km., whereas at 3 300 km. the best frequencies were 50 and 150 cycles.

Reception of the doubly-modulated signals shows that, when the control frequencies have been adjusted to correspond to the sky-ray path-differences, the phase-fading is eliminated. This removes all of the deep troughs of fading, and the residual intensity variations are then well within the capabilities of simple automatic-volume-control apparatus at the receiver.

(1) Introduction.
    (*a*) Phase and intensity fading.
    (*b*) Locations of transmitter and receivers.
    (*c*) Summary of short-distance experiments.
(2) Two Modulations in Suppressed-Carrier Transmissions.
    (*a*) Fading of d.c. component of rectified signal.
    (*b*) Fading of audio-frequency components of rectified signal.
(3) Experiments in Melbourne.
(4) Experiments in Perth.
(5) Conclusions.
(6) Acknowledgments.
Appendix. Identification of Sky Rays.

(1) INTRODUCTION

(*a*) Phase and intensity fading

In another paper* it has been shown that the fading of radio signals can be controlled by experimental methods which depend on transmissions being made at adjacent frequencies. The whole of this preliminary work was carried out at a distance from the sending station such that the intensities of the ground and sky rays were comparable. Under these simple conditions the intensity of the received signal at night is proportional to

$$\epsilon_0^2 + 4\epsilon_s^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

whereas the uncontrolled signal is determined by

$$\epsilon_0^2 + 4\epsilon_s^2 + 4\epsilon_0\epsilon_s \cos\theta \quad . \quad . \quad . \quad . \quad (2)$$

where ϵ_0, ϵ_s respectively are the vertical components of the electric forces in the ground and sky rays and θ is the phase-difference between them. The effect of the control is therefore to remove phase-fading and to prevent the night-time signal from falling below that which is due to the ground wave alone. The residual fading is then to be ascribed to intensity variations in ϵ_s, so that the night-time signal intensity fluctuates between the limits ϵ_0^2 and $(\epsilon_0^2 + 4\epsilon_s^2)$. Residual fading of this amount is of little importance since the total range of variation in the signal intensity falls within the limits of automatic-volume-control (A.V.C.) apparatus.

On the other hand, the maximum and minimum intensities of a signal subject to phase fading are $(\epsilon_0 \pm 2\epsilon_s)^2$. When the ground- and sky-ray signals are comparable, the troughs of fading are so deep that the residual signal falls below the noise level and the application of A.V.C. methods is of little avail. At the same time, the disappearance of the carrier wave involves considerable distortion in telephonic transmissions since the side-waves are then left to beat with each other and to produce harmonics of the wanted programme tones.

In long-distance communication, where reception is confined to sky rays, the same principles apply with little modification. In general it is found* that at least two sky rays are present, so that the received signal, in its simplest form, is proportional to

$$\epsilon_1^2 + \epsilon_2^2 + 2\epsilon_1\epsilon_2 \cos\theta \quad . \quad . \quad . \quad . \quad (3)$$

In this case, both ϵ_1 and ϵ_2 are subject to amplitude variations, so that, even when phase fading has been eliminated, the signal may fluctuate between zero and $(\epsilon_1^2 + \epsilon_2^2)$. Fortunately, however, ϵ_1 and ϵ_2 seldom have zero intensity simultaneously, and in practice the residual $(\epsilon_1^2 + \epsilon_2^2)$ is usually of sufficient strength to actuate a receiver fitted with A.V.C.

This point will be made clear by an examination of Fig. 1, in which there is a comparison of controlled and uncontrolled transmissions. The detector in the receiver was adjusted to saturation point, the effect of which is to place a limit on the galvanometer deflection. Thus all signals above a certain threshold value will produce the same galvanometer reading, while deflections below this amount will indicate deep troughs of fading during which the maximum amplification available in the receiver is insufficient. In Fig. 1(*a*) the uncontrolled signals fell below the threshold value approximately 20 times per minute, whereas in Fig. 1(*b*) the failures were only about 5 per minute. Both records were taken at a distance of 700 km. from the transmitter, the mean frequency being 3·46 Mc.

---

* A. L. GREEN and G. BUILDER: "Control of Wireless Signal Variations" (see page 610).

* See E. V. APPLETON and A. L. GREEN: *Proceedings of the Royal Society*, A, 1930, vol. 128, p. 159; also T. L. ECKERSLEY: *Journal I.E.E.*, 1932, vol. 71, p. 405.

In the long-distance experiments the authors have attempted to reduce the frequency of occurrence of the deep troughs of fading and have assumed that A.V.C. technique will be available to smooth out the residual fluctuations.

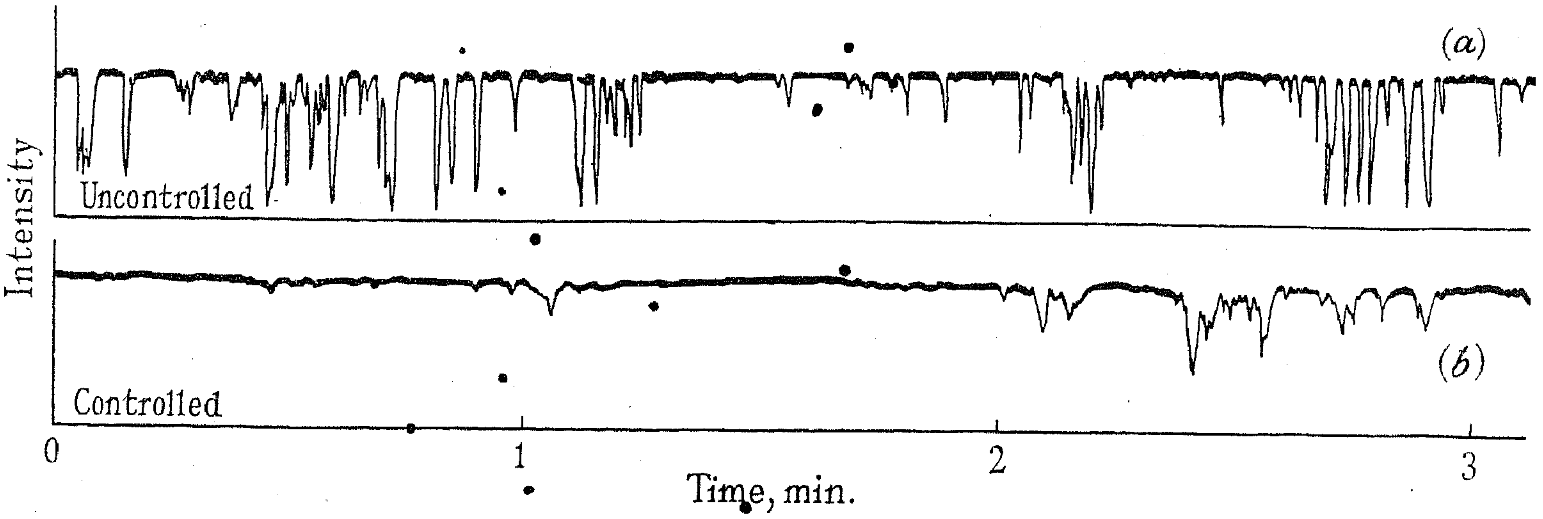


Fig. 1.—Comparison of (*a*) uncontrolled and (*b*) controlled signals, frequency 3·5 Mc., distance 700 km., 9.30 p.m. (E.S.T.) 13th February, 1935. (The receiver included a limiter, so that the record shows only the troughs of the fading.)

In the short-distance experiments the amplitude of the fading was defined by the quantity

$$A = \frac{I_{max.}^2 - I_{min.}^2}{I_{max.}^2 + I_{min.}^2} \times 100 \quad . \quad . \quad . \quad (4)$$

where $I_{max.}^2$ and $I_{min.}^2$ are the maximum and minimum values respectively, during a cycle of fading, of the d.c. component in the output of the square-law detector in the receiver. On this basis there is 100 per cent fading when the signals due to the ground and sky rays are equal and when the troughs of fading go to zero. When reception is confined to sky rays a better picture of the efficiency of a communication circuit is, however, obtained by considering the intensity of the signal at a fading trough as compared with the mean signal. We therefore define a "factor of constancy" of the signal,

$$K = \frac{\text{Minimum}}{\text{Mean}} \times 100 \quad . \quad . \quad . \quad . \quad (5)$$

such that a perfectly steady signal has a constancy factor of 100. We may then state arbitrarily that there is a deep trough of fading when K falls below 10. In practice it is found that unmodulated signals frequently give values of K as low as unity, but that in the controlled transmissions K seldom falls below 10.

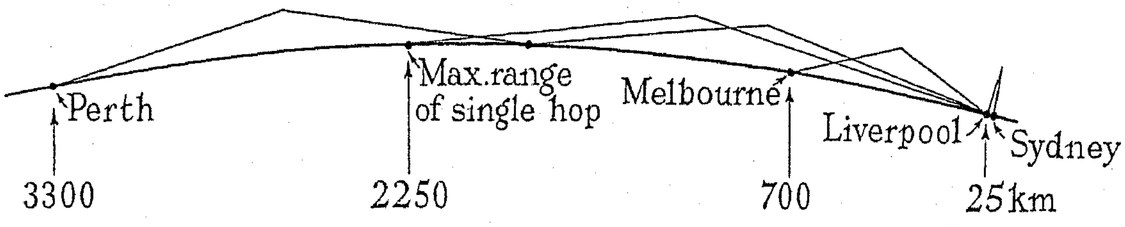


Fig. 2.—Sky-ray paths between transmitter at Sydney and receivers at Liverpool (N.S.W.), Melbourne (Victoria), and Perth (W.A.).

(*b*) Locations of transmitter and receivers

Fig. 2, which is drawn roughly to scale, shows the sky-ray paths between the transmitter at Sydney (New South Wales) and the receivers. The short-distance measurements were made at Liverpool (N.S.W.), at a distance of 25 km. from the transmitter; the medium-distance measurements at Melbourne (Victoria), at 700 km.; and the long-distance at Perth (Western Australia), at 3 300 km.

The short-distance measurements, which have been described in a previous paper,* were carried out with the object of verifying the theory of fading control under experimental conditions for which the related ionospheric phenomena are well understood.

The receiver was next moved to Melbourne, and the experiments repeated using sky-ray reception alone. Now it is known† that in the case of the Sydney–Melbourne circuit there is normally present a strong singly-reflected ray from the E region whose path-length is sensibly independent of the height of the Kennelly–Heaviside layer. This ray was therefore used as a reference by which to measure the path-differences with the subsidiary sky rays and hence to adjust the fading-control system to the prevailing ionospheric conditions.

In selecting Perth as the site for the long-distance measurements, use was made of the fact that the maximum range* which may be attained by a singly-reflected ray from the E region is about 2 200 km. At greater distances than this, therefore, reception must be by multiple-reflected rays, so that the measurements which were made at a distance of 3 300 km. are representative of long-distance propagation.

---

* *Loc. cit.*

† D. F. Martyn, R. O. Cherry, and A. L. Green: *Proceedings of the Physical Society*, 1935, vol. 47, p. 340.

By doing the experiments in three stages it was found that much additional data became available. The elucidation of the sky-ray paths for the Liverpool and Melbourne sites makes it possible to determine the critical angle which demarcates E-region reflections from F-region reflections. With this knowledge it then becomes feasible to hazard a guess as to the identities of the multiple-reflected rays received at Perth. The adjustment of the fading-control apparatus is not dependent on this knowledge but, since it is of interest in connection with the mechanism of long-distance propagation, it has been included in the Appendix to this paper.

(*c*) Summary of short-distance experiments

The most satisfactory type of fading-control transmission was found to be a suppressed-carrier modulated signal. Thus, if ω_r and ω_q are respectively the radio and control angular frequencies, the signal at the receiver due to the ground ray alone is proportional to

$$\epsilon_0 \cos \omega_q t \sin \omega_r t \quad . \quad . \quad . \quad . \quad . \quad (6)$$

Similarly, the sky-ray signal at the receiver is

$$2\epsilon_s \cos (\omega_q t + \chi) \sin (\omega_r t + \theta) \quad . \quad . \quad . \quad (7)$$

and it has been shown that the phase angles χ and θ are determined by

$$\left.\begin{aligned} \theta &= -\ \omega_r D/c \\ \chi &= -\ \omega_q D'/c \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad (8)$$

where c is the velocity of propagation in free space, and D and D' are respectively the optical and equivalent path-differences between the ground and sky rays.

On combining the ground- and sky-ray signals and passing them through a square-law detector, the change in direct current in the detector anode circuit is proportional to

$$\epsilon_0^2 + 4\epsilon_s^2 + 4\epsilon_0\epsilon_s \cos \theta \cos \chi \quad . \quad . \quad . \quad (9)$$

Hence it follows that phase fading, which is due to variations in θ, can be eliminated by ensuring that $\cos \chi = 0$. The condition for fading control is therefore

$$\frac{\omega_q}{2\pi} = \frac{(2n+1)}{4} \cdot \frac{c}{D'} \quad . \quad . \quad . \quad . \quad (10)$$

where n is any integer. The control modulation frequency is determined by the path-difference between the interfering rays and is independent of the mean frequency of the wave, except so far as D' itself is a function of ω_r.

The conclusions derived from the short-distance investigation which are relevant to the present paper are:—

(i) Theoretically it is possible to eliminate phase fading completely when the control frequency is adjusted to correspond to the path-difference between the interfering rays. In practice, fading greater than 60 per cent was easily reduced to less than 5 per cent.

(ii) The odd harmonics of the control frequency are also available for the purpose of reducing fading.

(iii) The control frequency is sensibly independent of the mean frequency of the transmissions. Minor variations in the height of the ionosphere and in the position of the receiver do not appreciably affect the degree of control.

(iv) In general it is necessary to read messages on such circuits by observing the change in direct current of the receiver output, since the audio-frequency components are uncontrolled.

Three problems therefore present themselves in the application of fading-control systems of this kind to long-distance propagation: First, it is necessary to measure the path-differences between the main sky-rays before it is possible to decide on the frequency of control modulation. Secondly, it would be desirable to supplement the control modulation at a single frequency by another which could be used to convey intelligence. Thirdly, since it is probable that the received signal will consist of more than two sky rays, it would be advantageous to provide additional control modulation at frequencies suitable for the subsidiary sky rays.

As to the first of these problems, it has been found that experiments of the Appleton–Barnett frequency-change type* are suitable for measuring the sky-ray path-differences. As regards the second and third problems, it will be shown that an effective compromise can be made for long-distance telegraphic communication by imposing two modulations at the transmitter and suppressing the carrier.

(2) TWO MODULATIONS IN SUPPRESSED-CARRIER TRANSMISSIONS

(*a*) Fading of d.c. component of rectified signal

If two modulations of equal amplitude but at angular frequencies ω_p and ω_q are imposed on the transmissions, and the carrier is suppressed, then the emitted signal is of the form

$$\epsilon (\cos \omega_p t + \cos \omega_q t) \sin \omega_r t \quad . \quad . \quad . \quad (11)$$

and the received signal has components at the four angular radio frequencies $(\omega_r \pm \omega_p)$, $(\omega_r \pm \omega_q)$, where ω_p and ω_q are small compared with ω_r. The phase difference between two sky rays at angular frequency ω_r is

$$\theta = -\ \omega_r D/c$$

and at angular frequency $(\omega_r + \triangle\omega_r)$ it is

$$\theta + \triangle\,\theta = -\ \frac{1}{c}(\omega_r D + D'\triangle\omega_r) \quad . \quad . \quad (12)$$

Hence, if $\triangle\omega_r$ is given the values $\pm\ \omega_p$, $\pm\ \omega_q$, it is then easy to show that the received signal is proportional to

---

* Throughout their experiments the authors have assumed that sky rays reflected from the E region traverse simple triangular paths. Since the ionization gradient is sharp (see D. F. Martyn: *Proceedings of the Physical Society*, 1935, vol. 47, p. 323) this assumption should not involve serious error.

* E. V. Appleton and M. A. F. Barnett: *Proceedings of the Royal Society*, A, 1925, vol. 109, p. 621.

$$\epsilon_1(\cos\omega_p t + \cos\omega_q t)\sin\omega_r t + \epsilon_2[\cos(\omega_p t + \phi) + \cos(\omega_q t + \chi)]\sin(\omega_r t + \theta) \quad (13)$$

where ϵ_1, ϵ_2 are the vertical components of electric force in the two main sky-rays, and

$$\left.\begin{aligned}\phi &= -\omega_p D'/c\\ \chi &= -\omega_q D'/c\end{aligned}\right\} \quad . \quad . \quad . \quad . \quad (14)$$

After the combined signal has been passed through a square-law detector, the change in direct current in the anode circuit is proportional to

$$\epsilon_1^2 + \epsilon_2^2 + 2\epsilon_1\epsilon_2\cos\theta\cos\tfrac{1}{2}(\phi+\chi)\cos\tfrac{1}{2}(\phi-\chi) \quad (15)$$

Supposing that the message is to be copied with the help of a d.c. relay, phase fading can be suppressed by adjusting to zero either $\cos\frac{1}{2}(\phi+\chi)$ or $\cos\frac{1}{2}(\phi-\chi)$. Looking at it in another way, it is possible to control interference between all sky rays whose path-differences satisfy the relation

$$D_1' = \frac{(2n+1)\pi c}{\omega_p + \omega_q} \quad . \quad . \quad . \quad . \quad (16)$$

where n is an integer, and also between another set of rays corresponding to

$$D_2' = \frac{(2n+1)\pi c}{\omega_p - \omega_q} \quad . \quad . \quad . \quad . \quad (17)$$

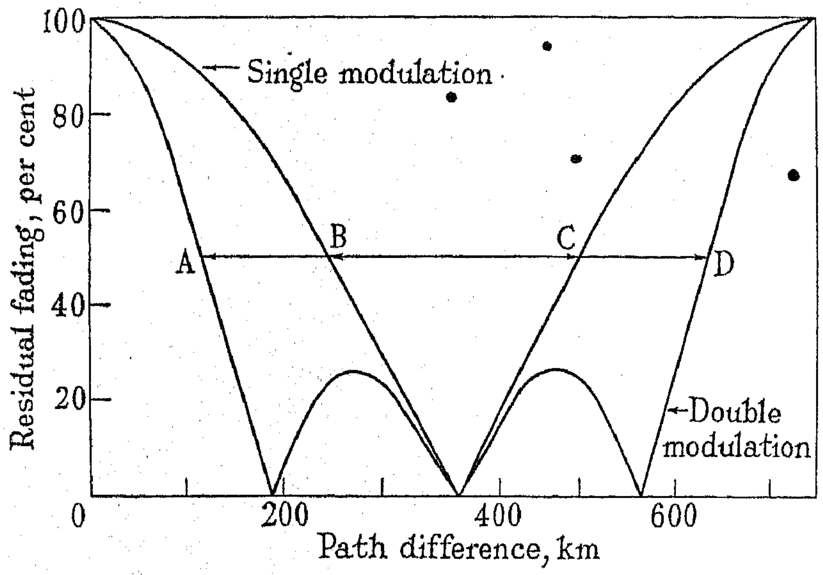


Fig. 3.—Calculated amounts of residual fading for a single control modulation at 200 cycles and for double modulation at frequencies of 200 and 600 cycles, with carrier suppression. (The ranges of effective control are BC and AD respectively, i.e. 250–500 and 115–635 km. of path-difference.)

Fig. 3 indicates the difference to be expected between the effects of single and double modulations. In one case the control frequency is 200 cycles and phase fading is eliminated when the equivalent path-difference is 375 km. If we assume that the two sky rays have equal intensities, then the residual fading should be less than 50 per cent for all values of D' between 250 and 500 km. With double modulation at frequencies of 200 and 600 cycles the range of effective control is 115 to 635 km. in D', and phase fading is completely suppressed for three values of D'—187·5, 375, and 562·5 km.

It is therefore clear that there is a considerable advantage in using two modulations when D' is not known accurately or when there are being received more than two interfering rays with comparable amplitudes. In the particular case for which Fig. 3 has been drawn, the frequencies of the two modulations are in a 3 : 1 ratio but it is obviously possible to vary the frequencies, both absolutely and relatively, in order to suit other ionospheric conditions. It has been found, however, that the 3 : 1 ratio is a convenient compromise in telegraphy between (i) the possibility of obtaining effective fading control of the d.c. component in the detector, for a large range of values of D'; and (ii) the desirability of using the audio-frequency components in the detector circuit for the purpose of reading the message.

The problem of the audio-frequency components in the rectified signal is somewhat complicated, so that it will be necessary to discuss the question in some detail.

(*b*) Fading of audio-frequency components of rectified signal

It has previously been shown that there is no control of the audio-frequency components of the signal in the output from the detector in the case of a single modulation. In fact, when the condition for control of the d.c. component is exactly satisfied, the intensity of the audio-frequency component is proportional to

$$\sqrt{(\epsilon_1^4 + \epsilon_2^4 + 2\epsilon_1^2\epsilon_2^2\cos 2\theta)}\cos 2\omega_q t \quad . \quad . \quad (18)$$

and the rapidity of fading is just double that for an unmodulated wave.

For a suppressed-carrier doubly-modulated wave, the received signal is given by (13), and the intensities of the audio-frequency components are proportional to

$$\begin{aligned}&\epsilon_1^2[\cos 2\omega_p t + \cos 2\omega_q t + 2\cos(\omega_p+\omega_q)t + 2\cos(\omega_p-\omega_q)t]\\ &\quad + \epsilon_2^2\{\cos 2(\omega_p t+\phi) + \cos 2(\omega_q t+\chi) + 2\cos[(\omega_p+\omega_q)t\\ &\qquad + (\phi+\chi)] + 2\cos[(\omega_p-\omega_q)t + (\phi-\chi)]\}\\ &\quad + 2\epsilon_1\epsilon_2\cos\theta\{\cos(2\omega_p t+\phi) + \cos(2\omega_q t+\chi)\\ &\qquad + 2\cos\tfrac{1}{2}(\phi+\chi)\cos[(\omega_p-\omega_q)t + \tfrac{1}{2}(\phi-\chi)]\\ &\qquad + 2\cos\tfrac{1}{2}(\phi-\chi)\cos[(\omega_p+\omega_q)t + \tfrac{1}{2}(\phi+\chi)]\} \quad . \quad (19)\end{aligned}$$

From (19) it follows that the audio-frequency components at angular frequencies $2\omega_p$ and $2\omega_q$ are uncontrolled, but that the $(\omega_p + \omega_q)$ signal can be controlled by making the adjustment $\cos\frac{1}{2}(\phi-\chi) = 0$. Alternatively we may use the $(\omega_p - \omega_q)$ tone if $\cos\frac{1}{2}(\phi+\chi)$ is made zero.

The special case, $\omega_p = 3\omega_q$, which has already been mentioned as providing good fading control of the d.c. component when more than two sky rays are being received, is also of interest here. On making the substitutions $\omega_p = 3\omega_q$, $\phi = 3\chi$, in (19) it may be shown that there are audio-frequency components at frequencies $2\omega_q$, $4\omega_q$ and $6\omega_q$, but that the $2\omega_q$ tone is the strongest. Considering this component alone, it may then be shown that the conditions for control are

$$\cos\chi = \pm\tfrac{1}{2}$$

Hence, phase fading in the $2\omega_q$ tone is eliminated for the two sets of sky rays which satisfy the relations

$$D' = \left(\frac{3n \pm 1}{3}\right)\cdot\frac{\pi c}{\omega_q} \quad . \quad . \quad . \quad . \quad (20)$$

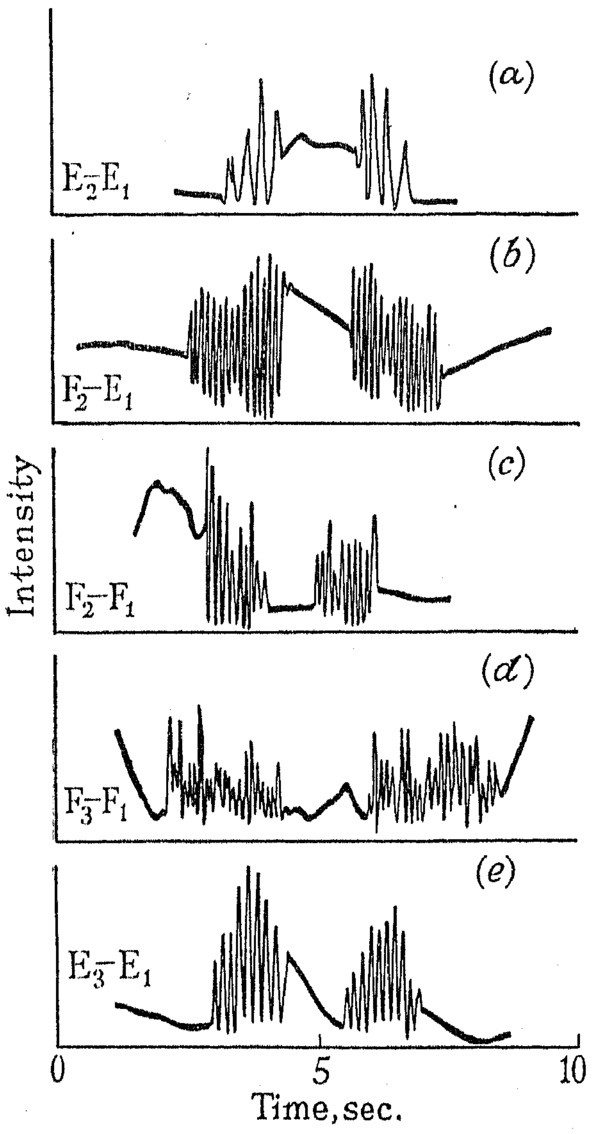


Fig. 4.—Typical frequency-change records obtained in Melbourne. Amount of frequency-change, 10·8 kc.; mean frequency, 3·46 Mc. (E_1 denotes singly-reflected ray from E region, E_2 doubly-reflected ray from E region, etc.)

Record	(a)	(b)	(c)	(d)	(e)
Number of fringes	3·7	15·5	10	25	9
Path-difference (km)	103	430	300	700	250
Sky rays	E_2–E_1	F_2–E_1	F_2–F_1	F_3–F_1	E_3–E_1

As in the case of the d.c. component, a wide range of values of D' can therefore be covered by the adjustment $\omega_p = 3\omega_Q$, and it has been found that considerable variations in the ionospheric conditions are possible without impairing the efficiency of the system.

(3) EXPERIMENTS IN MELBOURNE

The mean frequency of the transmissions was 3·46 Mc. ($\lambda \simeq 87$ metres). A few records were also obtained at 7 Mc., but it was found that, at this frequency, Melbourne was within the skip distance after 9 p.m. (E.S.T.). However, the results recorded at 7 Mc. only differed from those obtained in the main series of tests by the relatively fewer subsidiary sky-rays observed at the higher frequency.

Tests of the Sydney–Melbourne circuit had been made in 1932 with the Appleton–Barnett frequency-change technique at a mean frequency of 1·45 Mc., when it had been found that there were invariably two or more sky rays present with comparable intensities. In the present tests similar results were immediately obtained. Reproductions from the photographs of typical sets of interference fringes are shown in Fig. 4, for which the amount of the frequency-change was 10·8 kc. The numbers of fringes produced by this change of frequency varied from 3·7 to 25, corresponding to values of the path-difference between the interfering sky-rays of 103 to 700 km. Fortunately, however, the path-difference did not vary erratically between these limits, and on a number of evenings the whole of the records could be sorted into two main groups for values of D' of about 100 and 500 km. In a later section, reasons will be given for supposing that in both cases the main sky-ray was that which had been reflected once by the E region and that the interfering rays were doubly-reflected, by the E and F regions respectively.

Figs. 5 and 6 show how the measured values of D' varied from night to night. In Fig. 5 are plotted the results for the 1st, 7th, and 14th February, 1935, when the propagational conditions were comparatively simple. For these days the path-difference was 100 km. during the sunset period, rising gradually to about 150 km. at 10 p.m.

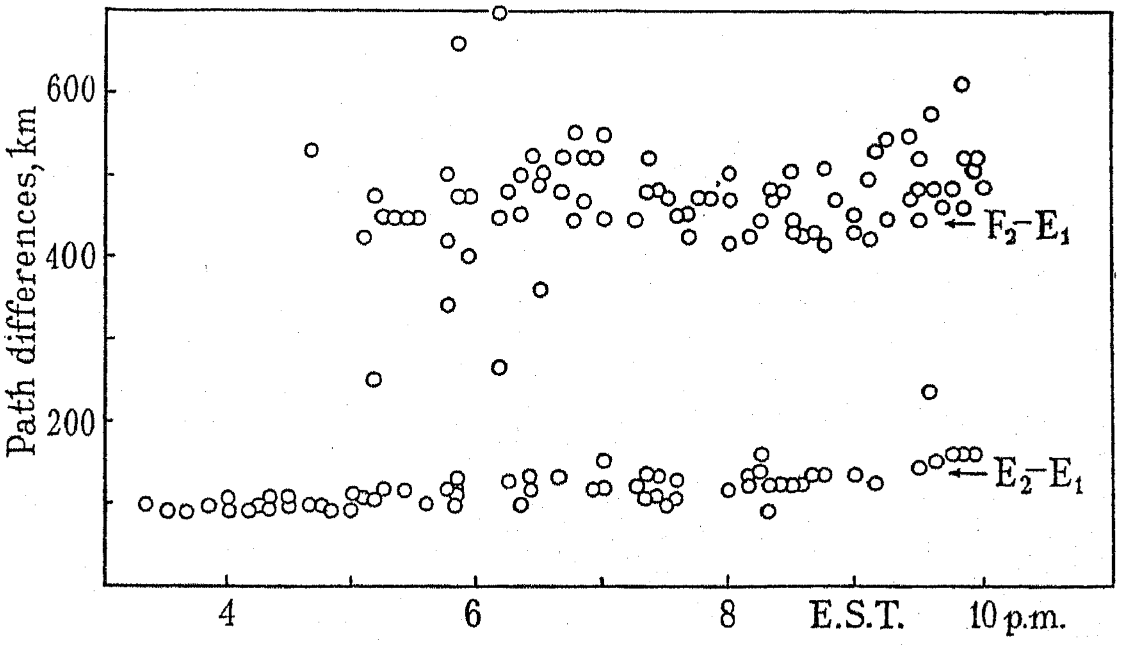


Fig. 5.—Path-differences measured in Melbourne on three nights—1st, 7th, 14th February, 1935.

(E.S.T.). At about 2 hours before sunset, however, there appeared subsidiary reflections with values of D' of about 500 km., and, as the evening advanced, such records were more frequently obtained.

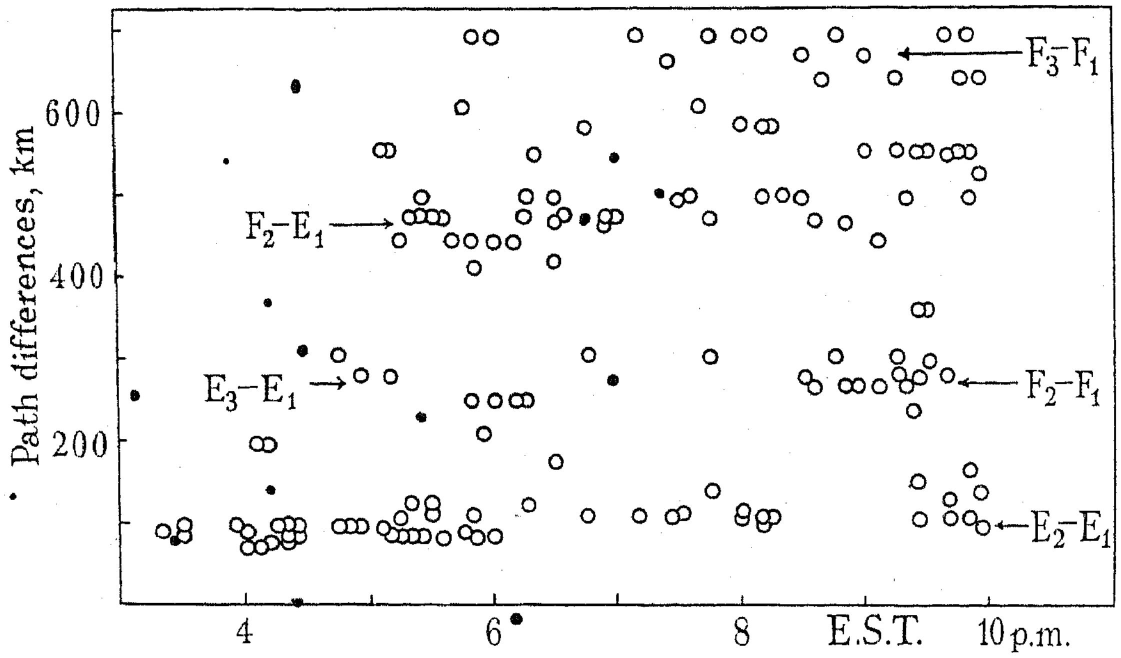


Fig. 6.—Path-differences measured in Melbourne on three nights—4th, 5th, 6th February, 1935. (Note that E_3–E_1 merges into F_2–F_1 after sunset.)

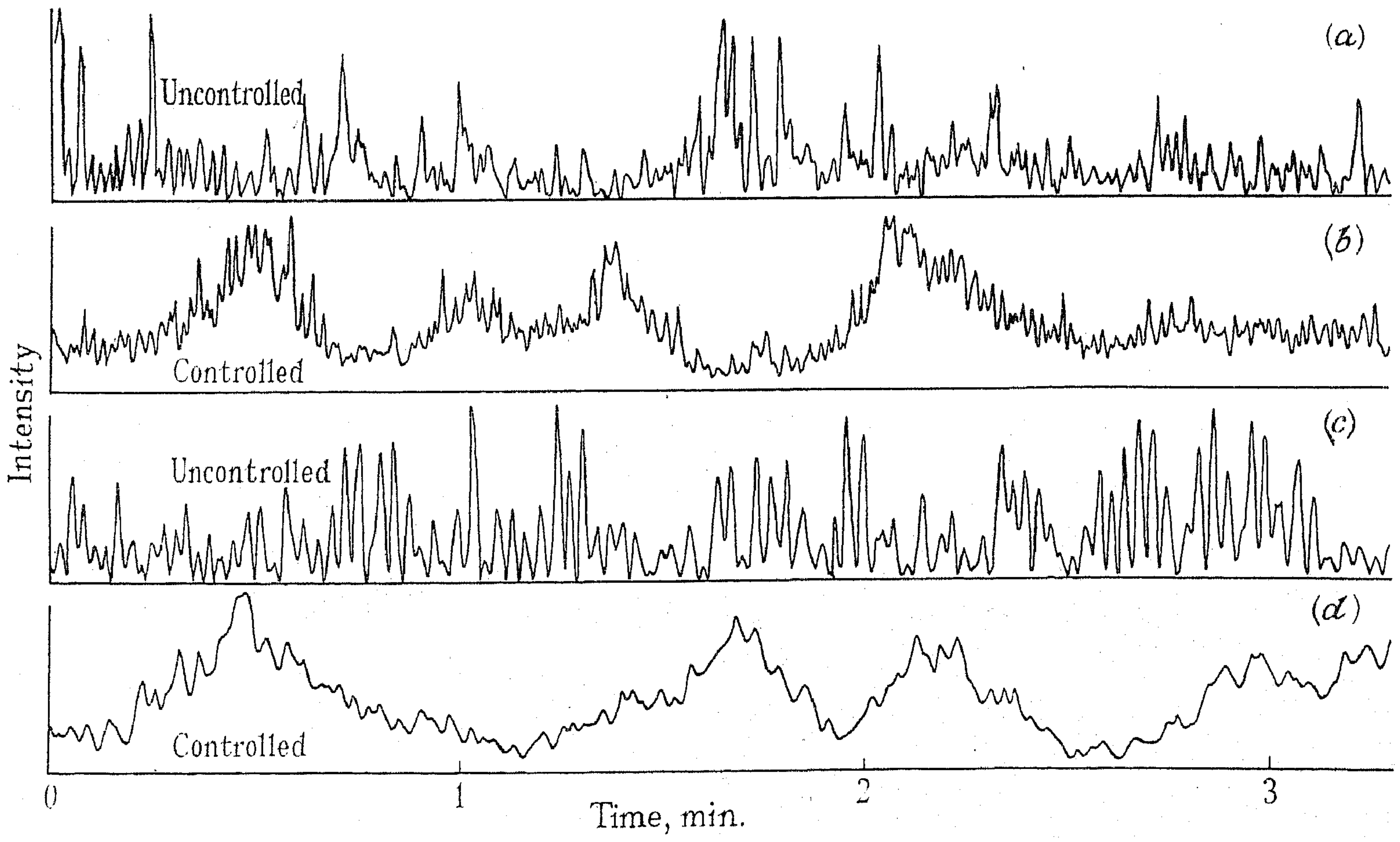


Fig. 7.—Melbourne: comparison of natural fading of modulated and unmodulated signals, 13th February, 1935. (*a*) 6.15 p.m., (*b*) 6.30 p.m., (*c*) 6.45 p.m., (*d*) 7.00 p.m., E.S.T. (The controlled signals were carrier-suppressed with 200 cycles modulation. The comparison shows a marked reduction of the fast fading.)

Fig. 6 is for the disturbed days, results being shown for the 4th, 5th, and 6th February, 1935. Groups of records showing the 100-km. and 500-km. path-differences were again obtained, but, in addition, there was an intermediate series at about 300 km. and also indications of path-differences greater than 600 km. Usually, however, the fringes corresponding to the abnormally long paths were small, so that the amount of interference with the main signal was not serious. On the other hand, the fringes which indicated the 300-km. path-differences were usually well marked and, in those occurring after about 8 p.m., the severity of the fading as well as the mean intensity was very high.

It is therefore clear that there are three important series of values of D' which should be allowed for when selecting the frequency of control modulation. A beginning was made with a control frequency of 200 cycles, corresponding to $D' = 375$ km., the object being to control the fast fading which is correlated with path-differences in the range 300–500 km.

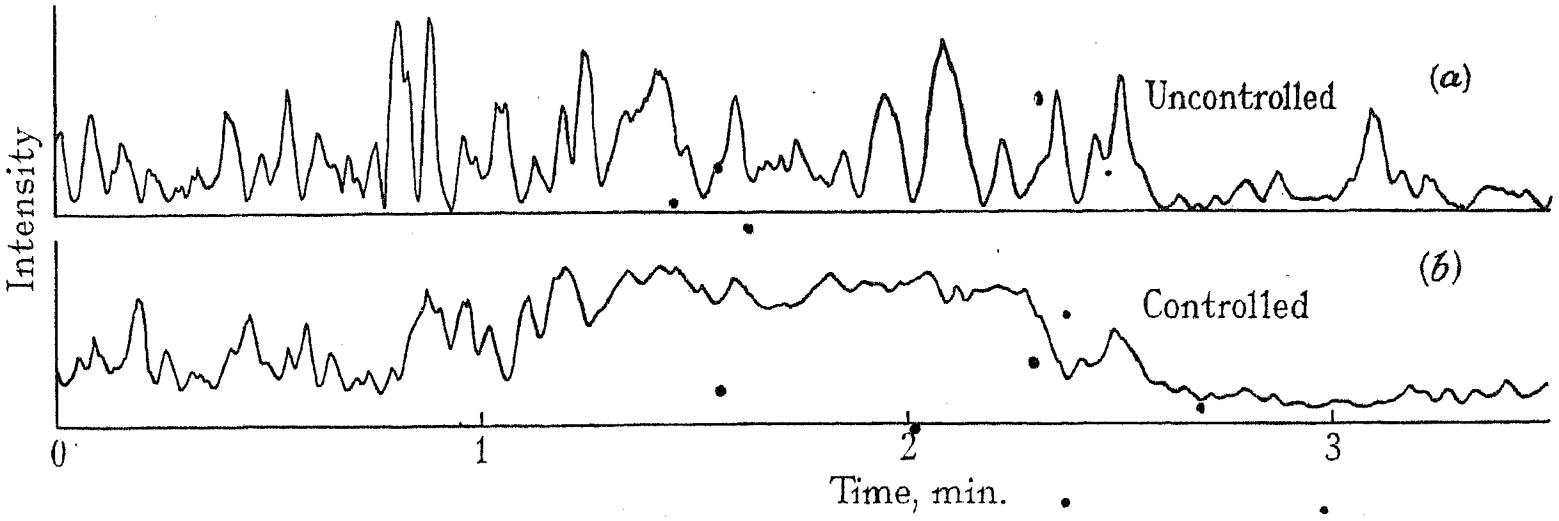


Fig. 8.—Melbourne: comparison of natural fading of unmodulated carrier with doubly-modulated suppressed-carrier, at frequencies of 200 and 600 cycles. (The effect of the control is to remove the deep troughs of phase fading. The residual fluctuations are probably due to variations in intensity of the sky rays.)

Typical records obtained with the single modulation of 200 cycles are shown in Fig. 7, in which there is a comparison of controlled and uncontrolled signals. Records (*a*), (*b*), (*c*), and (*d*), were obtained during successive periods of 15 minutes on the 13th February, 1935, beginning at 6.15 p.m. (E.S.T.). In records (*a*) and (*c*), deep troughs of fading were occurring at the rate of about 15 per minute and the transmission circuit was of very little use for carrying intelligence. On the other hand, it will be seen that the fast fading has been so much reduced in records (*b*) and (*d*) that the troughs occur at the rate of rather less than 1 per minute. A further improvement is also to be noticed in that the smallest value of the constancy factor is about 10 per cent, whereas in the uncontrolled records the same factor frequently falls below 1 per cent. It is to be concluded that the addition of the 200-cycle control modulation is sufficient to reduce the fading to an amount which is well within the capabilities of A.V.C. apparatus.

In other records taken at about the same time, however, it was noticed that the slow fading was occasionally severe. This result is to be expected, since no efforts have been made to control the phase fading corresponding to path-differences of about 100–150 km. In addition, the slow fading may in part be due to variations in the intensities of the sky rays. An attempt was therefore made to differentiate between these alternatives by imposing two modulations on to the suppressed-carrier signals, at frequencies of 200 and 600 cycles, the latter corresponding to $D' = 125$ km.

Typical extracts from the double-modulation photographs are given in Fig. 8, both records being obtained between 8 p.m. and 9 p.m. on the 15th February, 1935. In record (*a*), deep fading troughs were observed at the rate of about 6 per minute and the constancy factor occasionally approached zero. On the other hand, there were no very deep troughs of fading in the controlled record, the minimum value of the constancy factor being about 15 per cent. A noticeable improvement is therefore obtained by using the double modulation, but it is to be concluded that there is a marked degree of intensity fading normally present in these transmissions since the residual fading is still great enough to require the addition of A.V.C. in the receiver.

(4) EXPERIMENTS IN PERTH

The mean frequency of the transmissions was again 3·46 Mc. for the majority of the tests carried out in Perth. At this frequency reception was only feasible after about 5 p.m. (West Australian Standard Time), when the whole of the path from Sydney was in darkness. However, it proved to be convenient to use this relatively low frequency for the fading-control experiments, partly because it enabled a comparison to be made with the Melbourne results and partly because it is known* that phase fading

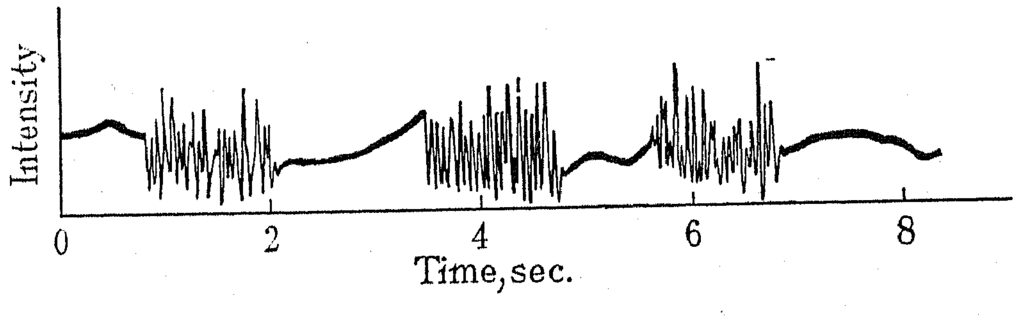


Fig. 9.—Typical frequency-change records obtained in Perth 6.45 p.m. (W.A.S.T.), 5th March, 1935. Amount of frequency-change, 8·6 kc.; mean frequency, 3·46 Mc.; number of fringes, 21; path-difference, 730 km.; sky rays F_5–$E_{2,3}$.

---

* T. L. Eckersley: *Journal I.E.E.*, 1929, vol. 67, p. 992.

is more severe at the lower frequencies on account of the presence of subsidiary multiple-reflected rays. In fact, the tests which were also made at frequencies of 7·5 and 9·1 Mc. showed that the propagational conditions were

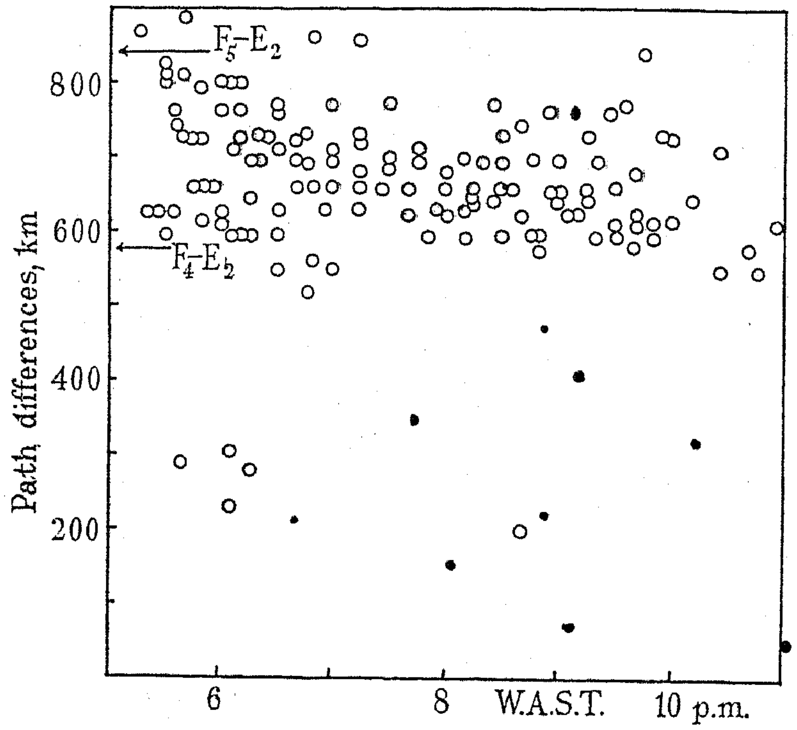


Fig. 10.—Path-differences measured in Perth, 4th, 5th, 6th, 7th, 8th March, 1935; mean frequency, 3·46 Mc.

noticeably simpler at the higher frequencies. It is therefore to be inferred that the choice of 3·46 Mc. for the operating frequency ensured that the tests were carried out under exacting conditions.

Reception of the frequency-change signals, which were used at the commencement of the tests in order to discover the path-differences between the main sky rays, disclosed that a considerable degree of phase fading was always present. Normally there were two main interfering rays with a path-difference of about 600–800 km, and, although this quantity varied somewhat erratically from minute to minute, yet on the whole the total range of variation was very much less than in the Melbourne experiments.

Fig. 9 is a reproduction of three sets of fringes recorded at 6.45 p.m. (W.A.S.T.) on the 5th March, 1935. The amplitude of the fringes shows that the two sky rays were of nearly equal intensity, and the number of fringes—about 21 for a frequency-change of 8·6 kc.—corresponds to a path-difference of 730 km.

In Fig. 10 are plotted the measured path-differences for the evenings of the 4th, 5th, 6th, 7th, and 8th March, 1935. It will be seen that almost the whole of the observations gave values of D' between 600 and 800 km., for which the corresponding frequencies suitable for the control modulation are 125 and 94 cycles. Accordingly the control frequency was fixed at 125 cycles for the first comparisons of the fading of unmodulated with suppressed-carrier signals.

Fig. 11 shows extracts from typical photographic records of natural fading during the period 6.00–7.40 p.m. (W.A.S.T.) on the 14th March, 1935. In records (*a*) and (*c*), taken with unmodulated signals, the fading was very fast, there being respectively 30 and 90 troughs per minute. Records (*b*) and (*d*), for the suppressed-carrier transmissions, indicate a very marked reduction of phase fading. No deep troughs are to be observed in these extracts, and the constancy factor of the circuit was

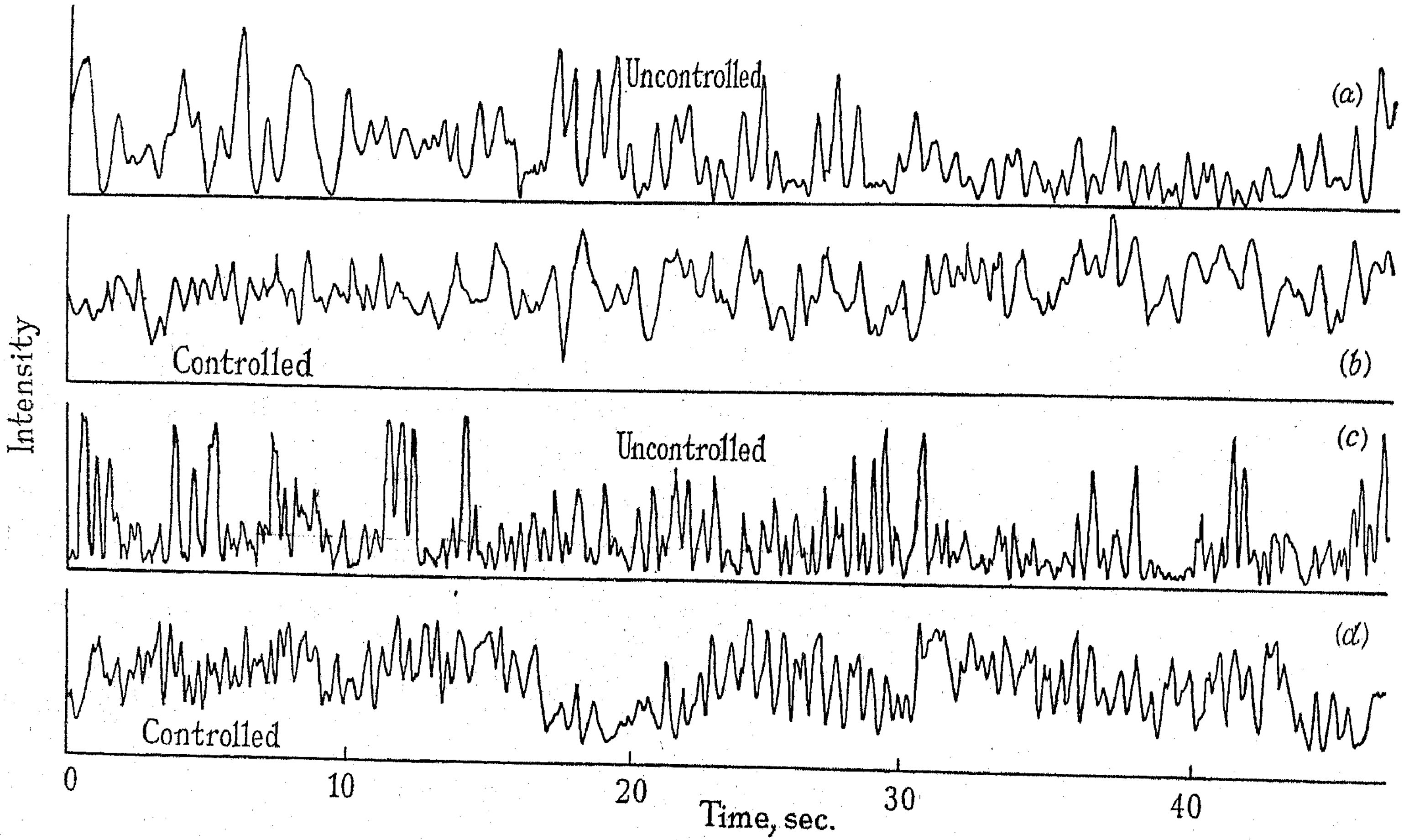


Fig. 11.—Comparison of natural fading of unmodulated carrier with that of suppressed-carrier system modulated at 125 cycles, on 14th March, 1935. (*a*) 6.10 p.m., (*b*) 6.00 p.m., (*c*) 7.40 p.m., (*d*) 7.30 p.m., W.A.S.T. (The controlled records show a marked reduction in the amount of fast fading.)

always above 25 per cent. In record (*d*), however, the character of the residual fading suggests that a further improvement might be made if the control could be adjusted more exactly to the path-differences between the sky rays. Accordingly a second series of tests was carried out with this object in view, the procedure being to use simultaneously two control modulations at frequencies of 50 and 150 cycles respectively.

In Fig. 12 there is shown a comparison of typical records obtained with the two systems, extract (*b*) being for single modulation at a frequency of 125 cycles, (*d*) being for double modulation of 50 and 150 cycles, and records (*a*) and (*c*) being the corresponding checks with unmodulated signals. From the (*a*), (*b*) pair it is seen that the fading control was generally good but that there were two periods of poor signal intensity at the beginning and end of record (*b*), when the constancy factor fell to about 10 per cent. On the other hand, in record (*d*) the least value of the constancy factor is about 30 per cent, this being typical of all the records obtained with the system of double modulation. A number of the double-modulation records showed an even greater constancy of signal, and it may be doubted whether the provision of A.V.C. in these cases could have much improved the intelligibility of the transmissions.

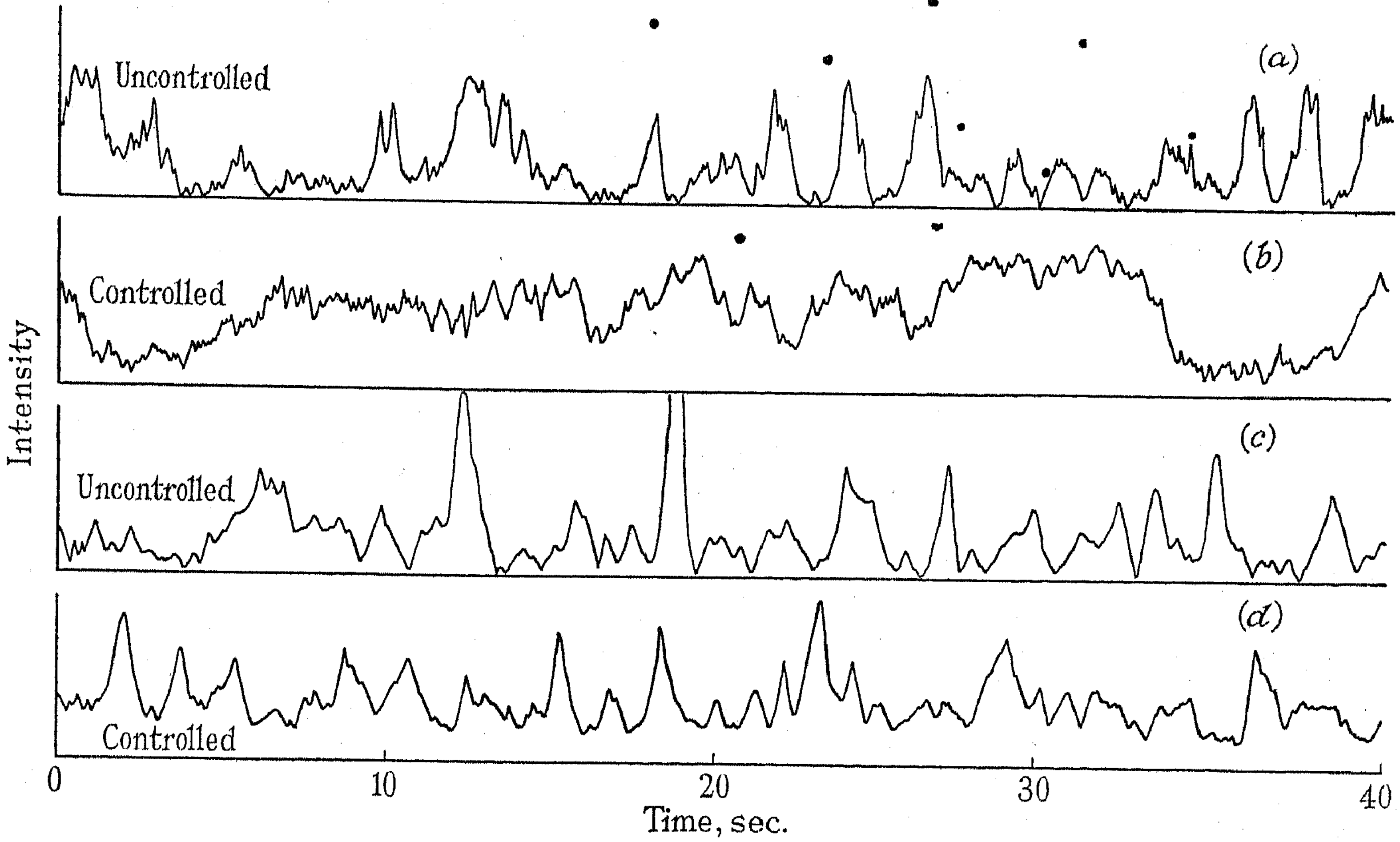


Fig. 12.—Comparison of natural fading of modulated and unmodulated signals. (*a*) 10.55 p.m., unmodulated carrier. (*b*) 10.35 p.m., suppressed-carrier modulated at 125 cycles. (*c*) 9.55 p.m., unmodulated carrier. (*d*) 9.40 p.m., suppressed-carrier doubly-modulated at 50 and 150 cycles.

(5) CONCLUSIONS

The present paper describes a continuation of fading-control experiments by methods which rely on transmissions being made at adjacent frequencies.

It has previously been shown that, at a distance between sender and receiver such that the ground ray has approximately the same intensity as the sky ray, the optimum conditions for the control of phase fading are obtained with suppressed-carrier transmissions when the modulation frequency is about 400 cycles. It was also shown that the frequency of control modulation is independent of the mean frequency of the wave and is inversely proportional to the path-difference between the ground ray and the main sky-ray.

Investigations at greater distances, 700 and 3 300 km., now show that the optimum control frequencies are determined by the path-differences between the interfering sky-rays. At a distance of 700 km. the path-difference was usually about 125 km. during the sunset period, and phase fading was traced* to interference between a singly-reflected ray (E_1) from the E region and a doubly-reflected ray (E_2); the corresponding control frequency is 600 cycles. Later in the evening the two main sky-rays were E_1 and F_2, the measured path-difference being about 500 km. and the optimum control frequency 150 cycles. Occasionally, however, path-differences were observed intermediate between the two important series at 125 and 500 km., and these were traced to interference between E_1 and E_3 soon after sunset and to F_1 and F_2 later in the evening. Under these circumstances it was found that a greater degree of fading control could be achieved by imposing two modulations on to the suppressed-carrier transmissions, the frequencies being 200 and 600 cycles.

At a distance of 3 300 km the measured path-differences were approximately 600–800 km. and the best results were obtained with two control modulations at frequencies of 50 and 150 cycles respectively. In this case it was found that a bundle of rays E_1, E_2, E_3, acts as a single equivalent wave with a path-length of about 3 400 km. The interfering ray from the F region is either F_4 or F_5, but on a few occasions both F rays are received in addition to the E wave.

---

* See Appendix.

Previously it had been found necessary to read messages on these circuits by observing the change in direct current in the output of the detector in the receiver, since the audio-frequency components are uncontrolled. The provision of two modulations, however, has the effect of removing this disability in addition to widening the range of path-differences over which effective fading control can be obtained. It has been shown theoretically, and verified experimentally, that the best compromise between these two factors is made when the modulations are in a 3 : 1 frequency ratio. When this condition is satisfied it is found that both the direct-current and the audio-frequency components in the anode circuit of the detector are controlled for a wide range of values of the path-difference.

It is now clear that fading-control systems of the type described are effective in reducing phase fading to negligible proportions. There still remain residual fluctuations of the signal due to intensity fading of the sky rays, and, theoretically, it is possible for the intensities of all the received sky rays to be zero simultaneously. In practice, however, it is found that the elimination of phase fading removes all the deep troughs of fading, and the residual intensity fluctuations are well within the capabilities of simple automatic-volume-control apparatus at the receiver.

(6) Acknowledgments

The investigation formed a part of the programme of the Radio Research Board of the Australian Commonwealth Council for Scientific and Industrial Research, with whose permission the paper is published.

Thanks are due to Mr. A. H. Mutton, B.E., for help at the transmitter, and to Messrs. J. O'Dea and N. F. Ollivier for help in establishing the Sydney–Perth circuit. The authors are greatly indebted to Prof. P. H. Fraenkel, of the University of Western Australia, for the provision of a receiving site in Perth; to Mr. H. P. Brown, C.M.G., M.B.E., Director-General of the Australian Postmaster-General's Department, for help at all stages of the work; and to Prof. J. P. V. Madsen, of the P. N. Russell School of Engineering of the University of Sydney, for his continued interest in the progress of the investigations.

APPENDIX

Identification of Sky Rays

Simultaneous measurements of the Sydney transmissions with the frequency-change technique by Martyn, Cherry, and Green, in Liverpool and Melbourne, disclosed that path-differences of about 100 km. measured in Melbourne are to be correlated with interference between singly- (E_1) and doubly- (E_2) reflected rays from the E region. Similarly, path-differences of about 500 km. have been traced to interference between the rays F_2 and E_1. Hence we may safely identify the sky rays in the present series of experiments by using similar considerations.

In Fig. 13 there are plotted sky-ray paths and angles of incidence for the Sydney–Melbourne circuit, assuming heights of 100 and 250 km. for the E and F regions respectively.* Using these curves to interpret the measurements of path-differences in Figs. 5 and 6, it is easy to show that the most commonly occurring pairs of sky rays producing phase fading were (E_2–E_1) and (F_2–E_1). On the disturbed days, shown in Fig. 6, phase fading could also be attributed at times to (E_3–E_1) and (F_2–F_1), both of these pairs giving path-differences of about 300 km. In addition there were some indications of (F_3–F_1) and path-differences of about 700 km.

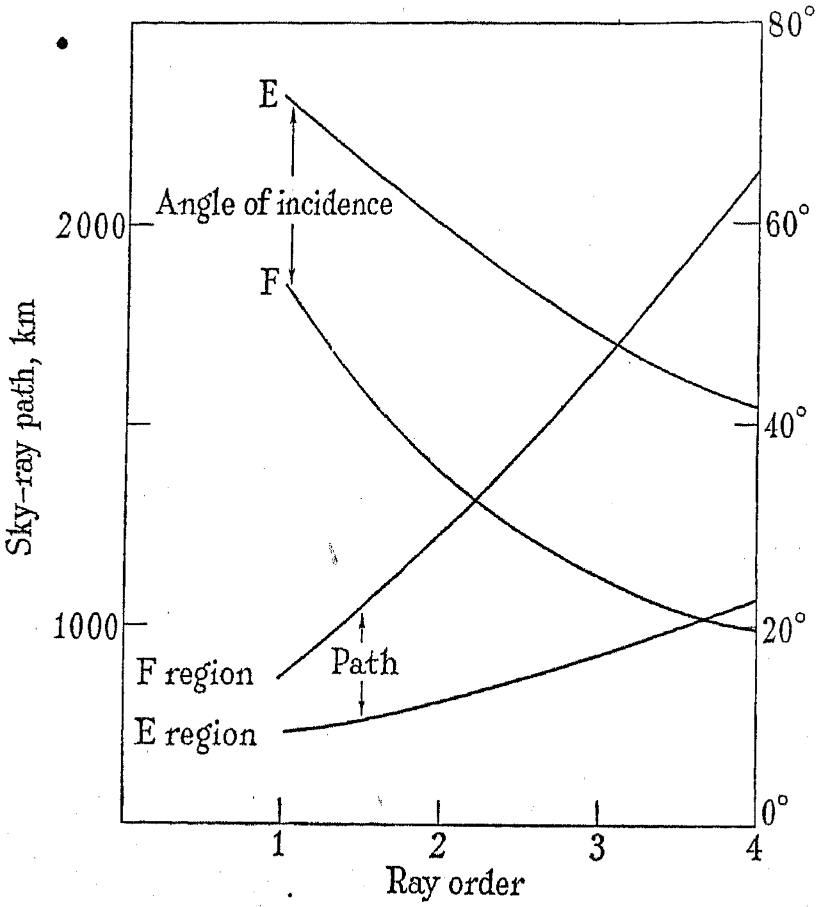


Fig. 13.—Calculated sky-ray path-lengths and angles of incidence for Sydney–Melbourne circuit, assuming E- and F-region heights of 100 and 250 km. respectively.

It is important to notice, moreover, that the critical angle of incidence which demarcates reflections from the E and the F regions was about 50° at this time of the year. This follows from the experimental evidence that the E_1, E_2, and F_2 rays were nearly always observed, the corresponding angles of incidence being 73°, 60°, and 35°. Hence, considering these rays alone, the critical angle must lie between 60° and 35°. Further measurements which demonstrate the occasional appearances of E_3 soon after sunset and F_1 later in the evening, close the gap to 49°–54°, so that the critical angle cannot be very different from 50° early in the evening, rising to 55° in the next few hours. This fact, and the more general consideration that both the E and the F regions are responsible for returning sky rays in long-distance transmissions, will be made use of in attempting to identify the sky rays received in Perth.

---

* It has also been assumed that the sky rays traverse simple triangular paths. The agreement found between theory and experiment indicates that, at night, the rays are not appreciably bent while passing through the E region and through the space between the E and the F regions. On the other hand, Hollingworth (*Proceedings of the Physical Society*, 1935, vol. 47, p. 843) finds bending during the daytime.

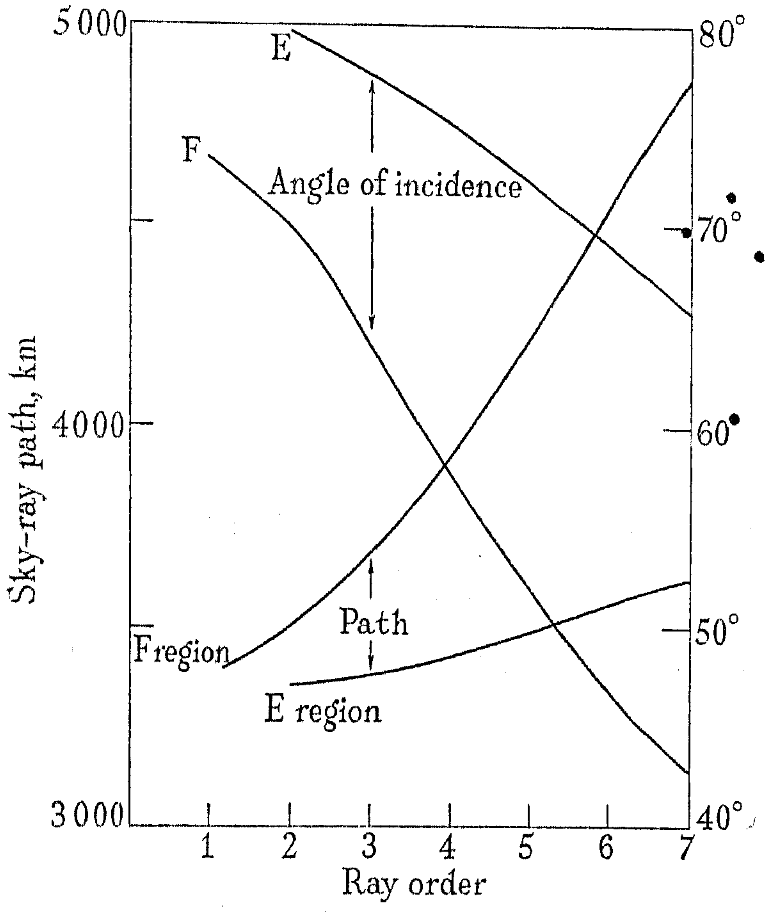


Fig. 14.—Calculated sky-ray path-lengths and angles of incidence for Sydney–Perth circuit, assuming E- and F-region heights of 100 and 250 km. respectively.

The great-circle distance between Sydney and Perth is 3 300 km., and the sky-ray path-differences and angles of incidence are plotted in Fig. 14. It is interesting to attempt to predict the path-differences which should have been observed in Perth and to make the comparison with the values determined by the frequency-change experiments.

Firstly, it may be noted that it is not possible to receive E_1 in Perth since the maximum range of a singly-reflected ray from the E region is about 2 200 km. Next, if the critical angle of incidence is about 50°, one would expect to receive E rays from the 2nd up to about the 15th order. Owing to loss of energy from repeated reflections at the earth's surface and at the ionosphere, however, it is unlikely that the intensities of the higher-order rays will be appreciable. Thus, in the case of the E region, we may expect a bundle of rays consisting of E_2 and E_3, and possibly E_4. Now from Fig. 14 the corresponding ray-paths are 3 360, 3 385, and 3 425 km., for which the path-differences are very small. Hence the phase fading between the E rays will probably be negligible and we can group them as a single equivalent sky ray with a path-length of about 3 400 km.

In the case of the F region, the critical angle of 50°–55° immediately eliminates the possibility of receiving F_1, F_2, F_3, and perhaps F_4, since such rays would be held down by the E region. For an F-region height of 250 km., which has been found suitable for the short- and medium-distance experiments, the path-lengths of the F_4 and F_5 rays are 3 920 and 4 190 km., and these are the rays which should most frequently be observed. Interference between either of these rays and the E ray of path 3 400 km. would give rise to path-differences of 520 and 790 km., so that we should expect to measure values of D' in the range 500–800 km. Comparison with the experimentally-observed path-differences of Fig. 10 shows that there is very good agreement between experiment and the hypothesis that phase fading is usually due to interference between F_4 and $E_{2,3}$ or between F_5 and $E_{2,3}$. As additional confirmation it may be noted that, if F_4 and F_5 are simultaneously received, there is the possibility of a path-difference being observed of about 300 km., and Fig. 10 shows that a few such values were occasionally noted.

DISCUSSION BEFORE THE WIRELESS SECTION, 6TH JANUARY, 1937, ON THE PAPERS* BY DRS. GREEN AND BUILDER (SEE PAGE 610) AND DRS. GREEN AND PULLEY (SEE PAGE 623)

Mr. W. L. McPherson: The value of the investigations described in the two papers is considerable from the point of view of ionospheric research, in which phase control of fading provides a definite improvement over the original technique. The value from the practical communication standpoint is, however, not so clear. The authors reduce fading by adjustment at both the transmitting and the receiving ends. At the transmitting end a particular form of emission is required, namely amplitude modulation, at a note frequency determined by the transmission conditions, together with suppressed carrier; while at the receiving end it is necessary to use a square-law detector, and in the majority of cases the useful part of the rectified signal is confined to the d.c. component, i.e. we are deprived of the use of note-frequency selection. Apparently to get the full benefit of the proposed system we must choose between a note frequency which will give a minimum of fading, and one which will be suitable from the normal interference standpoint in admitting the use of note selectivity by means of audio-frequency filters.

An item of rather special interest is the application of the authors' results to direction-finding and beacon work. The unreliability of the ordinary beacon and direction-finder at night has long been known, and one attempt to overcome it has been the introduction of the Adcock aerial system on both beacon transmitters and receiving direction-finders. The use of the Adcock aerial system is, however, not practicable on board ship, and it may be that the application to transmitting beacons of the principles disclosed in the paper would be of considerable value to ships fitted with direction-finders. A factor which might influence considerably this particular application is the possibility of having aural rather than galvanometer reception, as apparently would be possible if double-frequency modulation were used as mentioned in connection with long-distance communication. In the section of their paper dealing with direction-finding Dr. Green and Dr. Builder discuss only single-frequency modulation, and I should like to know whether they consider that the double-frequency modulation system could be usefully applied in this case, particularly with a view to aural reception. If the system is restricted to galvanometer reception of the detector d.c. component, the prospects of its general adoption do not seem very hopeful. Alterations to the receiving equipment would be involved in so many ships that there would be a good deal of hesitation before shipowners would commit themselves to the expense entailed.

---

* The papers were read by Mr. J. A. Ratcliffe, M.A., on behalf of the authors.

The authors state that the method they have developed for reduction of phase fading is not readily applicable to radio-telephony, yet the problem of phase fading is just as serious in radiotelephony as in radiotelegraphy. A number of attempts have already been made to solve it, the most general being the use of various diversity reception schemes with distributed aerial systems, the receiver being either fed from all the aerials simultaneously, so as to deliver an " average " signal, or perhaps automatically switched to whichever aerial happens to be the most effective at a given moment.

An alternative method now being investigated is the use of aerial arrays the directivity of which, in the vertical plane, is made so sharp as to permit reception along only one path. The interfering wave, which has traversed a different path, usually arrives at an angle sufficiently different from the " main " wave to enable effective discrimination to be made between them by virtue of the aerial directivity. Such a system requires some means of adjusting the vertical directivity, since the angle of arrival of the incoming wave is bound to vary; this can be obtained by controlling the phase-changes in the connections between the receiver and the elements of the array.

It is general experience that in radiotelephony the main trouble with phase fading occurs when the carrier component fades out. If the carrier is resupplied locally, in synchronism with the incoming carrier, a very high percentage of the fading will disappear. This is confirmed by observations made some years ago in the course of experiments relating to the relative advantages of single-side-band and full-wave systems; full-wave reception was always materially improved by the addition of local carrier, even though such accuracy of synchronization as is now contemplated was not then obtainable. Use of " local carrier " reception is therefore still another method by which phase fading can be reduced. In common with the sharply directional aerial and the diversity reception system, it is applicable to both radiotelegraphy and radiotelephony, and involves no special requirements at the transmitting end. The ultimate solution of the phase-fading problem seems more likely to lie along one of the three alternative lines of attack just mentioned than along the more restricted line dealt with in these papers.

Dr. R. L. Smith-Rose: I should like to refer to the fact that the authors are indebted for at least part of their early training and experience to the British Radio Research Board, and it is gratifying to see that they are carrying on the traditions of the work in which they were brought up in this country.

One of the main points of interest in regard to the papers is that they confirm so completely and neatly deductions which have been drawn from our present knowledge of the ionosphere. A good deal of patience and organization is necessary to get experimental results such as are described here between stations separated, as in some cases they were, by 2 000 miles or so.

One of the chief criticisms of the application of this work to a practical communications circuit is that a number of conditions have to be satisfied. For instance, it is necessary to know the distance, and also the height of the effective layer of the ionosphere, and if that height is going to vary appreciably from time to time the modulation frequency must be suitably altered in order to maintain the control; thus, to apply the authors' work to a communications circuit it appears to be essential to keep a complete record of ionospheric conditions in order to get the maximum controlling effect.

Those of us who are responsible for using direction-finders will not think a great deal of the polar diagrams which are given in Fig. 10 of the paper by Dr. Green and Dr. Builder as being representative of what can be done to-day with modern direction-finders. They are, of course, intended to show what improvements can be effected if a loop direction-finder is used. Except in the case of certain mobile receiving systems, however, such as those of ships or aircraft, it is not necessary to use a loop direction-finder. It is possible that direction-finding on ships provides a chance to apply the authors' suggestions practically, because ship direction-finders operate very largely on beacon signals intended solely for that purpose. The stations which transmit these signals are at present fitted for modulated continuous-wave emission, and if it were merely a question of selecting a particular modulating frequency it would be simple to apply the authors' idea straight away; but the real difficulty is that the distance between the receiver and the transmitter is variable, and not known at the time when the bearing is most required. The modulation frequency can only be right for one specific distance, apart from any other factors brought in by the variations in the ionosphere. Similar remarks apply in general to the analogous case of the rotating-beacon transmitter.

In thinking over this question of the possible application of the authors' work to direction-finding it has occurred to me that here is the possible answer to a discussion which went on amongst direction-finding investigators several years ago over the suggestion that the night errors of loop direction-finders were very much worse in the case of continuous-wave signals than with spark or modulated continuous-wave transmissions.* I was then of the opinion that, taking a general view from a large mass of miscellaneous data, there was no obvious difference between the accuracy of direction-finders used with continuous-wave and with modulated continuous-wave transmissions; but I can now see that it is possible that different investigators may, in certain cases, have had the conditions so adjusted, using modulated continuous-wave transmission, that their errors really were less than in the general case of continuous-wave transmissions.

---

* R. L. Smith-Rose: *Journal I.E.E.*, 1925, vol. 63, p. 923.

In the application to broadcasting, as the authors have realized, there is the same difficulty of having to adjust the modulation frequency according to the distance over which it is desired to operate. Essentially in broadcasting, all the receiving sets are distributed over a wide area, and one cannot satisfy the control conditions for the receivers all at once; but, as Fig. 11 shows, one might be able to improve the general conditions, if it is not possible to meet the ideal case in every instance.

Mr. R. Naismith: Fundamentally, this problem of phase fading arises from the existence of two or more paths along which the energy may flow from the transmitter to the receiver. The difference in the lengths of these paths introduces a time factor which is used as the basis of a method, described several years ago,* to assist in the solution of this problem. It is quite obvious that if we can receive all the energy coming by the shortest path before we receive any of the energy coming by the next shortest path, we can have no phase fading. The principle of the method is to send the energy in the form of an interrupted continuous-wave signal in which the interruptions both in recurrence and in duration are related to the main paths followed by the energy in travelling from the transmitter to the receiver. This method has several potential advantages: it tackles the problem at its source and therefore increases the efficiency of transmission, it has great flexibility, and it may be used to discriminate against random noise.

Drs. A. L. Green and G. Builder and **Drs. A. L. Green and O. O. Pulley** (*in reply*): Mr. McPherson's doubts as to the possibility of making practical use of the spaced-frequency method of controlling phase-fading are irrelevant to the objects of the investigation under discussion. In the "Introduction" to the first paper† we made it clear that the object of the research, particularly that concerned with short-distance propagation, was to make a fundamental investigation of the problem of communication on spaced frequencies and to develop an experimental technique by which fading control could be achieved. No attempts were made to compare the usefulness of the spaced-frequency method with the results already achieved in other known systems, e.g. diversity reception with spaced aerials, vertical directivity steering, or local carrier insertion, and it is our opinion that the final solution of the problem of minimizing fading must lie in combining the good points of all of the available systems rather than in relying on one method alone. This attitude finds considerable support from the practice, already common in long-distance telegraphy, of using the combination of a wobbled carrier at the transmitter with space diversity in the aerials at the receiver.

In relation to diversity systems, it is of interest to notice that the spaced-frequency method of controlling fading is essentially a frequency-diversity system, and that it has the very considerable advantage of giving a maximum of improvement in the steadiness of the received signal for a minimum of diversity. This achievement is inevitably linked with the necessity to adjust the technique in accordance with the prevailing ionospheric conditions, and it is easy to see that the other type of diversity, with spaced aerials, requires a corresponding adjustment if it is to be equally efficient.

In reply to Mr. McPherson and to Dr. Smith-Rose, we were somewhat unprepared for the amount of discussion on the possibility of applying the spaced-frequency method to direction-finding. In a paper of this kind it is proper to call attention to possible applications of the fundamental method, but it is left to the specialists concerned to work out the details. At this stage it is probably sufficient to point out that, although the optimum conditions are only achieved when the technique has been precisely adjusted to the particular ionospheric conditions, yet the addition of suppressed-carrier modulation can in no case have an adverse effect on the steadiness of the signal or on the accuracy of a bearing and, on the average, there must be a definite improvement for the majority of the users of the service.

In connection with Dr. Smith-Rose's 10-year-old problem of the differences between modulated and unmodulated signals for direction-finding, it is gratifying that the fundamental investigation of spaced-frequency transmissions is capable of supplying a satisfactory answer in favour of the modulated wave.

A more exact knowledge of the mechanism of spaced-frequency propagation has also supplied the solution to a problem* encountered in some early work of the Australian Radio Research Board in which an unsuccessful attempt was made to use 100-metre waves in the Appleton–Barnett frequency-change method of measuring ionospheric heights. On no occasion were sky waves detected, and it was concluded that the properties of the ionosphere over Australia were very different from those previously measured in England. The true solution, however, is that the transmitter on H.M.A.S. "Platypus" used in these tests employed full-wave self-rectified alternating current at a frequency of 500 cycles per sec. for the anode supply of the output valves, with the result that the outgoing signals were fully modulated at a frequency of 1 000 cycles per sec. The recent work now under discussion shows that this frequency of modulation is close to the optimum for suppression of phase interference and of the Appleton–Barnett artificial fading.

In reply to Mr. Naismith, the pulse method of eliminating phase-fading deserves more consideration than it appears yet to have received. It has, however, a number of disadvantages, among which are the wide frequency spectrum required for the transmission of very short pulses and the difficulty of applying the system to telephony.

---

* British Patent No. 422468.

† "Control of Wireless Signal Variations."

* "Australian Radio Research Board: Second Annual Report," *Journal of the Council for Scientific and Industrial Research*, (Melbourne), 1930, vol. 3, p. 156.

OPTIMUM SYMMETRICAL LIGHT DISTRIBUTIONS*

By H. R. S. McWHIRTER, B.Sc.(Eng.), Associate Member.

(*Paper first received* 10*th September, and in final form* 3*rd December,* 1936.)

SUMMARY

Certain symmetrical light distributions described briefly by the author in a previous paper are here considered at greater length. They possess, among other properties, that of producing uniform illumination on the horizontal plane in large lighting systems. The effect of varying the spacing/height ratio in a given system is here dealt with. Alternative methods of testing lighting fittings are described. The conclusion is reached that these light distributions may in some cases be regarded as the best that could be employed in practice, and in others as approximately the best. It is pointed out, however, that uniformity of illumination is often only one of a number of requirements that have to be met, and practical light distributions may be modified by this consideration and by the desirability of obtaining a high luminous efficiency.

(1) INTRODUCTION

If a lighting unit free to move in a vertical line only is suspended over a horizontal plane, any point on the plane will have maximum illumination produced on it when the line joining the point to the lighting unit makes a certain angle with the downward vertical. This angle is the value of θ for which the function $I \sin^2 \theta \cos \theta$ is a maximum, where I is the luminous intensity of the lighting unit at angle θ from the downward vertical.

In a previous paper† the author has shown that this angle (denoted by μ) may be used to calculate values of spacing/height ratio for the lighting unit. For example, in the case of four symmetrical lighting units suspended at equal heights at the corners of a square of fixed size over a horizontal plane, the illumination on the plane at the centre of the square would be a maximum when the length of side of the square was $\sqrt{2} \tan \mu$ times the mounting height of the lighting units. This formula when applied to well-known practical light distributions was found to yield values of spacing/height ratio in close agreement with those actually employed in practice. It was also found possible to construct polar distribution curves representing symmetrical light distributions that would produce uniform illumination on the plane in large systems in which the value of spacing/height ratio was as given by the above formula. These curves were termed "optimum polar curves."

The term "dispersive angle" was applied to the angle μ, and it was pointed out that it could be found experimentally.

In the present investigation the optimum polar curves are first slightly modified to improve the uniformity of illumination attained. Their properties are then described in greater detail, and the results of varying the value of spacing/height ratio in certain installations are considered. Alternative methods of determining the dispersive angle experimentally are described. In the final Section the optimum and practical polar curves are compared, and the circumstances are discussed in which the former may be considered to be the best possible shape for the latter. It is shown that, in practice, lighting units have often to fulfil other requirements besides that of producing uniform illumination on the horizontal plane, and that these, together with the desirability of a high luminous efficiency, should be borne in mind when considering a practical light distribution. The light distributions described herein are therefore not suitable for every purpose, and the term "optimum" is applicable to them in only a restricted sense.

(2) CONSTRUCTION OF OPTIMUM POLAR CURVES

In the following account of the method of constructing these curves, units of various quantities such as length, illumination, etc., are not mentioned, as it is only the numerical values that are of interest in the present instance. Any consistent system of units could be applied to the numerical values given.

Let Fig. 1 represent the plan of part of a large lighting system, the small circles representing lighting units arranged in the square formation and illuminating a large horizontal plane below. Let the curve TUH in Fig. 1A be the contour curve of illumination on the plane produced by one lighting unit, its ordinates representing to scale the illumination along a straight line on the plane passing vertically under the lighting unit, which is assumed to be suspended above the point S. The base-line SH represents the diagonal of a square such as L_1L_3 in Fig. 1. The 21 ordinates in Fig. 1A are marked 0 to 20 respectively at their feet, and they divide the base-line SH into 20 equal parts. Along each ordinate is written two numbers; the first gives the length of the ordinate, and the second, in brackets, gives the product of this with the number at the foot of the ordinate.

The curve KUV in Fig. 1A is such that its ordinates are inversely proportional to the square of its abscissae; and the fact that the contour curve touches this at U, and at all other points lies below it, ensures that PS subtends the dispersive angle at the lighting unit. A proof of this may be found in the author's previous paper.† FUA is the common tangent to the curve KUV and the contour curve.

---

* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of The Institution not later than one month after publication of the paper to which they relate.

† *Journal I.E.E.*, 1936, vol. 78, p. 699.

† *Loc. cit.*

The lengths of the ordinates of the contour curve were found by trial and error, and they are such that the illumination on the plane in Fig. 1 due to all the lighting units is as uniform as possible. The values of illumination at the "test points" L_1, E, F, G, H, K, M, N, P, Q, R, S, and T, in Fig. 1 are on or between the limits 4·005 and 3·995. These test points are such that they divide the sides of the triangle L_1HP into four equal parts, and T is the centroid of the triangle. The possibility of giving the values of illumination at the test points to three decimal places, and the lengths of the ordinates of the contour curve to four, is due to the fact that the contour curve was first drawn to a large scale, and when its shape had been finally determined by the condition that the illumination at the test points must be as nearly equal as possible, the values of the ordinates were all divided by the value of the mid-ordinate at P, thus making the latter unity. The values of illumination at the test points quoted above are of course the result of a similar division, the only object of which was to simplify the arithmetical work.

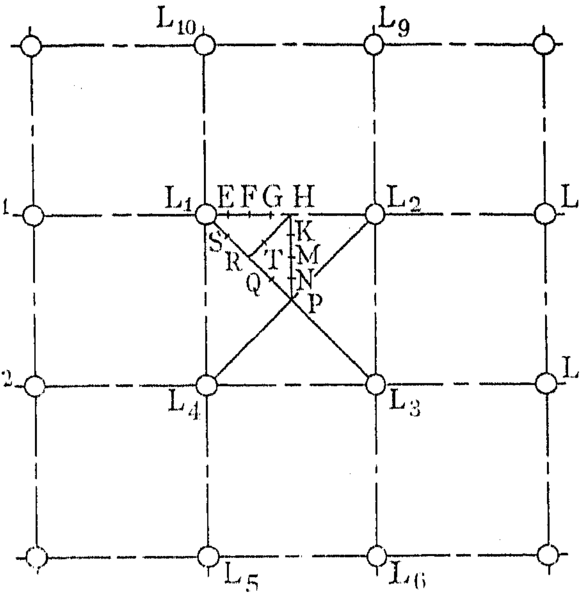


Fig. 1

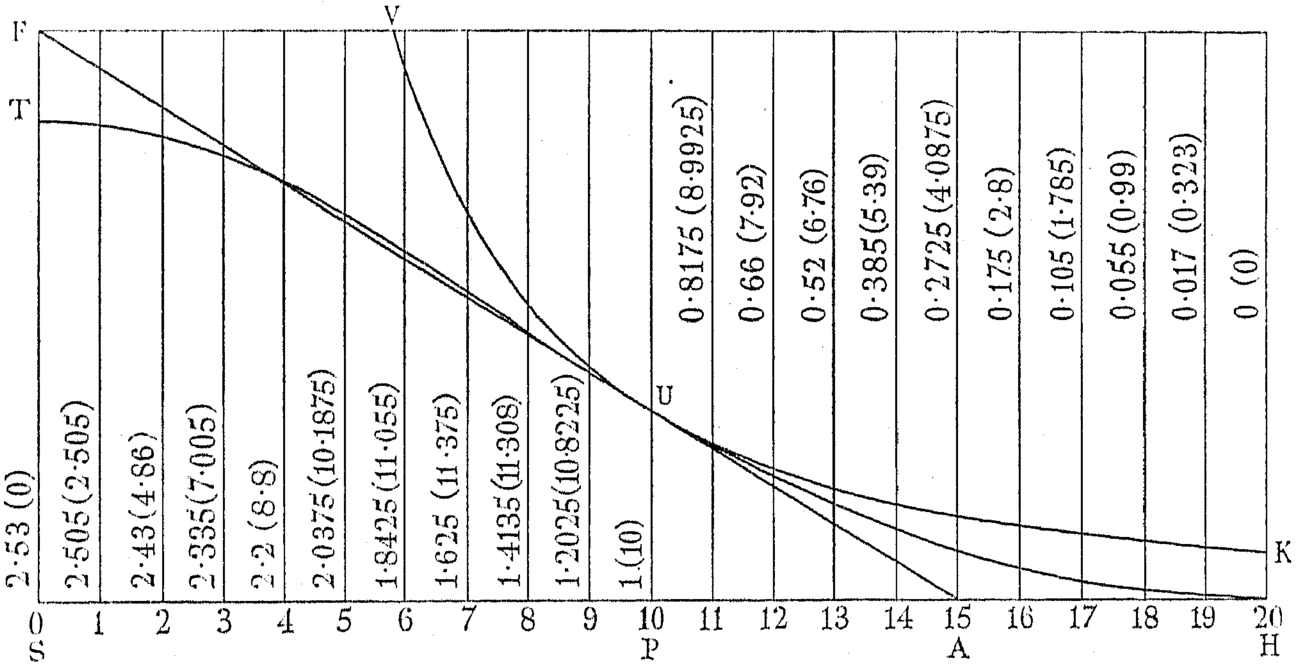


Fig. 1A

A comparison of this curve with that given in the author's previous paper* will show but very slight difference between them. Such difference as exists is to be accounted for by the greater uniformity of illumination attained in the present case. The uniformity ratio in the present instance is 99·75 %, as against 97·25 % attained previously.

As the values of illumination at the test points given above are those due to light coming direct from the lighting units only (i.e. with no addition for light reflected from a ceiling), the average illumination over the plane due to this direct light should agree in value with that at the test points. This average illumination can be found from the quantity of luminous flux emitted by one lighting unit. Referring to Fig. 1A, if E is the illumination at distance l from the point S the luminous flux from one lighting unit will be given by $2\pi\int_0^{20} Eldl$. The value of the integral would be the area under a curve on base-line SH (Fig. 1A) having ordinates corresponding in position to those of the contour curve but of length given by the figures in brackets on those ordinates. There is no necessity to draw this curve to find its area, as, the number of ordinates being odd, it may be found by applying Simpson's rule to the figures in brackets. The area so found, taking the length of the base-line SH to be 20, proves to be 127·206, which gives $127{\cdot}206 \times 2\pi = 799{\cdot}26$ as the quantity of luminous flux. The average illumination over the plane would be obtained by dividing this quantity of flux by the area of the plane associated with each lighting unit in Fig. 1, i.e. by the area of a square whose diagonal is 20 (the diagonal being equal to SH on Fig. 1A). Hence the average illumination is 799·26 divided by 200, i.e. 3·9963. The agreement with the values at the test points is thus excellent, as it lies between the limits found at those points. This value for the average illumination is of great accuracy, the only approximate process employed during its derivation being the use of Simpson's rule to evaluate the area; and as the number of ordinates was as high as 21 and the bounding curve, if drawn, would be found to be smooth, this error may be neglected.

---

* *Loc. cit.*

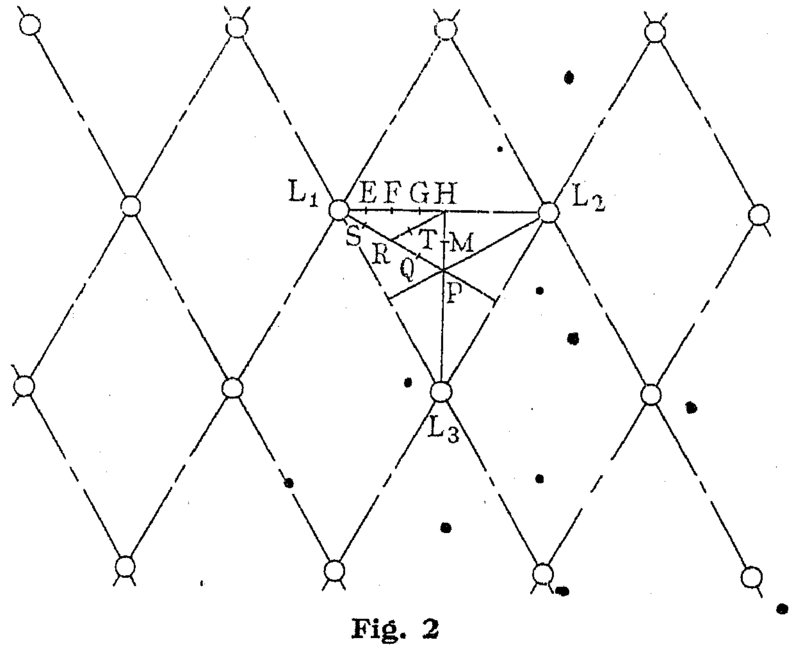


Fig. 2

With reference to the area evaluated by Simpson's rule, 65·4 % of it lies to the left-hand side of the mid-ordinate at P in Fig. 1A, and hence the same percentage of the luminous flux is similarly located.

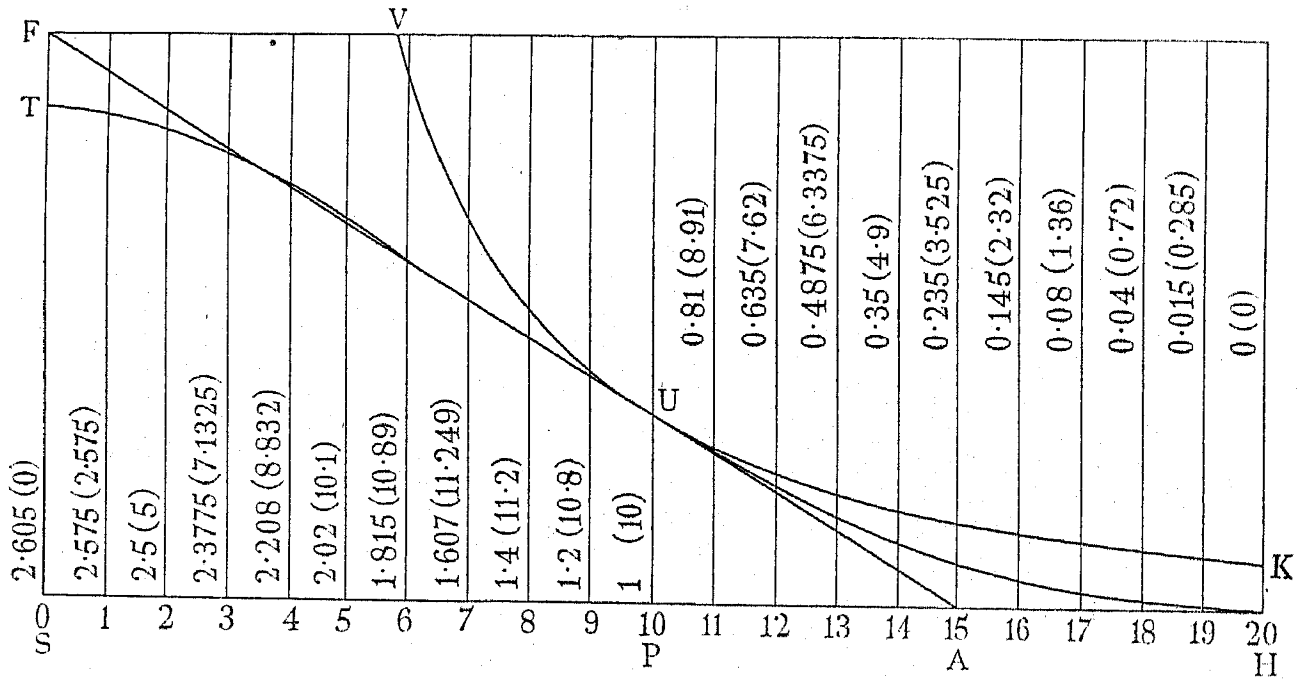


Fig. 2A

The illumination along any straight line in the plane in Fig. 1 would be derived from a number of lighting units; and if the illumination from each were plotted along the line as a base, the sum of the values of illumination at each point should of course be constant. It follows from this that the algebraic sum of the slopes of the various curves at each point should be zero. By applying this condition to the point L_1, considering it as being in the straight lines $L_{10}L_1L_4$ and $L_9L_1L_{12}$, it is possible to prove that the slope of the contour curve TUH in Fig. 1A must be zero at T and H.

To construct a polar curve having the dispersive angle μ from this contour curve, the lighting unit must be assumed to be at a height vertically above S such that PS subtends this angle at the lighting unit. The luminous intensity I at any angle θ from the downward vertical may then be found from the equation

$$I = \frac{100E}{\tan^2 \mu \cos^3 \theta}$$

where E is the illumination produced on SH by light emitted at this angle. The coefficient 100 appears in the formula as the result of assuming SH to be 20 units in length.

The selection of the arrangement of lighting units in Fig. 1 for the purpose of producing uniform illumination was quite arbitrary, and it was therefore considered advisable to ascertain whether it could be produced with the lighting units arranged as in Fig. 2, in which they are placed at the corners of rhombuses having an acute angle of 60°. The test points in this figure are L_1, E, F, G, H, M, P, Q, R, S, and T, which divide the two longer sides of the triangle L_1HP into four equal parts and the shortest side into two equal parts, and T is the centroid of the triangle. The contour curve in this case is shown in Fig. 2A, of which the base-line SH represents to scale twice the length L_1P in Fig. 2, and all the other features bear a precisely similar explanation to those of Fig. 1A. The results obtained by this contour curve may be summarized thus:—

Maximum illumination at the test points..	3·005
Minimum illumination at the test points..	2·995
Uniformity ratio	99·67 %
Average illumination calculated from luminous flux	2·999
Percentage of total flux on left-hand side of mid-ordinate	67 %

In this case also the slope of the contour curve at T and H (Fig. 2A) can be proved to be zero.

Polar curves can of course be obtained from this curve in the manner already described in connection with Fig. 1A.

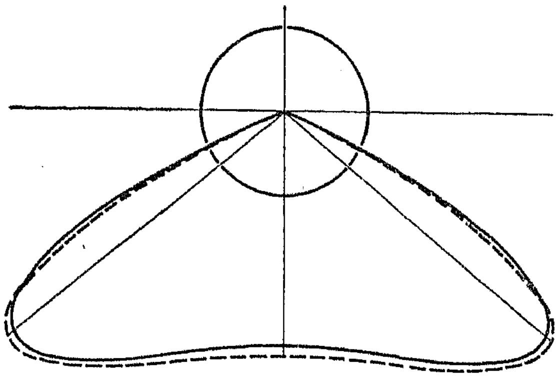


Fig. 3

$\mu = 50°$

In Fig. 3 two polar curves are superimposed, that in full lines being obtained from Fig. 1A, and the dotted curve from Fig. 2A. Both curves have the same dispersive angle (50°) and the same quantity of luminous flux. The curves are so similar that it seems unnecessary to investigate the properties of such curves derived from both Figs. 1A and 2A, as these properties would be very similar. In what follows, therefore, only polar curves derived from Fig. 1A will be considered. The reasons for this selection are firstly that the disposition of lighting units shown in Fig. 1 is more frequently encountered than that shown in Fig. 2; and secondly that the consideration of the latter disposition of lighting units involves the introduction of more complicated and less familiar formulae for the spacing/height ratio.

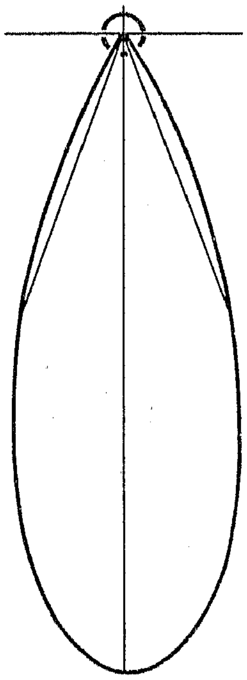


Fig. 4

$\mu = 19° 28'$
$\alpha = 54° 44'$
$n = 0{\cdot}5$

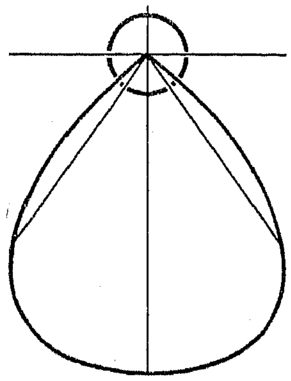


Fig. 5

$\mu = 35° 16'$
$\alpha = 35° 16'$
$n = 1$

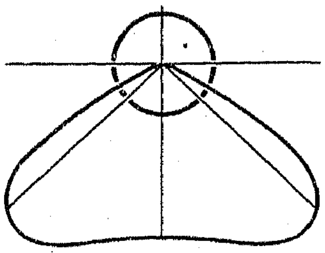


Fig. 6

$\mu = 46° 41'$
$\alpha = 25° 14'$
$n = 1{\cdot}5$

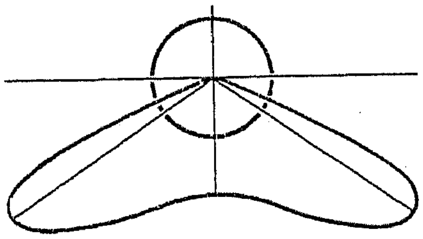


Fig. 7

$\mu = 54° 44'$
$\alpha = 19° 28'$
$n = 2$

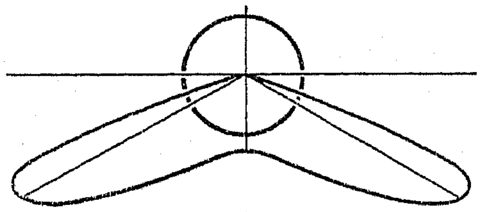


Fig. 8

$\mu = 60° 30'$
$\alpha = 15° 48'$
$n = 2{\cdot}5$

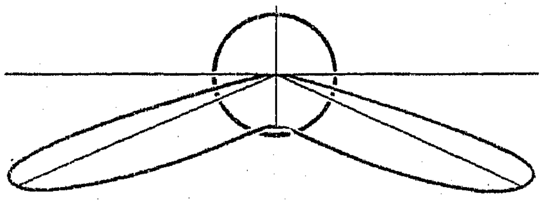


Fig. 9

$\mu = 64° 46'$
$\alpha = 13° 16'$
$n = 3$

(3) PROPERTIES OF OPTIMUM POLAR CURVES

Optimum polar curves for values of spacing/height ratio of 0·5, 1, 1·5, 2, 2·5, and 3, respectively, derived from Fig. 1A, are shown in Figs. 4 to 9 inclusive. Superimposed on each is the circle representing mean spherical candle-power, and radii vectores are drawn at the dispersive angle. Below each is written the value of the dispersive angle μ, the angle of cut-off α, and the spacing/height ratio n.

It has been explained that n is given by the formula $\sqrt{2} \tan \mu$. The angle of cut-off is the maximum angle below the horizontal within which no light is emitted, and from information in the preceding Section there will be no difficulty in seeing that this is given by $\cot \alpha = 2 \tan \mu$.

It may also be seen from the preceding Section that in all these curves 65·4 % of the luminous flux is emitted below the dispersive angle and 34·6 % above it, and that the vertical radius vector must be a normal to the curve.

Inspection of these curves shows that they consist of one lobe when the value of spacing/height ratio is low and two when it is high, the intermediate condition occurring when it is approximately 1·5. The curve for this condition (Fig. 6) is consequently somewhat flat on the underside. The proportion of the area of the curve above the dispersive angle increases as the spacing/height ratio is increased.

(4) APPLICATION IN LARGE LIGHTING SYSTEMS

To complete the investigation of the performance of these light distributions in large systems it is necessary to consider the effect of varying the spacing/height ratio in a given installation.

If a lighting unit were placed in the centre of each of the squares such as $L_1L_2L_3L_4$ in Fig. 1, these additional lighting units would in themselves form a system identical with Fig. 1. If, therefore, the lighting units in Fig. 1 produced uniform illumination, that due to the additional lighting units would also be uniform and hence the total illumination on the plane would remain uniform. The spacing/height ratio would be reduced, however, to $1/\sqrt{2}$ times its previous value. The process may obviously be repeated indefinitely, so that the optimum polar curves produce uniform illumination when the spacing/height ratio n is $\sqrt{2}\tan\mu$, $\tan\mu$, $(1/\sqrt{2})\tan\mu$, $\frac{1}{2}\tan\mu$ . . . etc. The largest interval between successive values in this series occurs between the first two, and it was therefore considered advisable to ascertain the uniformity ratio for values of n between these two. The results obtained were as follows:—

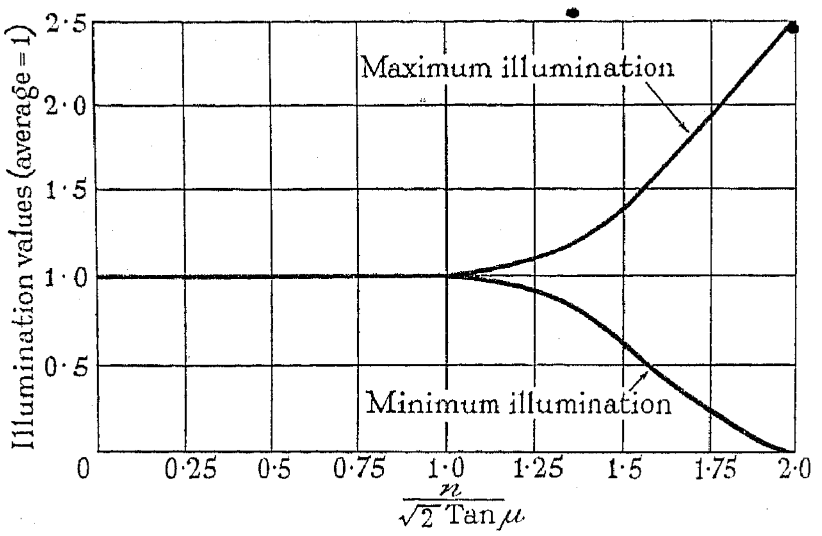


Fig. 10

When $n = 1{\cdot}239\tan\mu$ uniformity ratio $= 96\ \%$
When $n = 1{\cdot}125\tan\mu$ uniformity ratio $= 97\ \%$

The uniformity ratio is the ratio of minimum to maximum values of illumination occurring among all the test points. The above values for it are sufficiently high to justify describing the illumination as uniform for practical purposes.

It may therefore be affirmed that the optimum light distributions produce uniform illumination, not only when the spacing/height ratio is $\sqrt{2}\tan\mu$ but also when it has any lower value.

In order to show the variation in illumination when n is greater than $\sqrt{2}\tan\mu$ Fig. 10 has been prepared. This figure shows values of maximum and minimum illumination occurring among all the test points, plotted as ordinates against values of $n/(\sqrt{2}\tan\mu)$ as abscissae, the value of average illumination being taken to be unity. The upper curve represents values of maximum illumination, and the lower curve values of minimum illumination. The two curves coincide when $n/(\sqrt{2}\tan\mu)$ is unity or less.

These curves show that the minimum illumination on the plane would be 70 % of the maximum when $n/(\sqrt{2}\tan\mu)$ had the value 1·34, and 50 % when it had the value 1·46. The former value for the uniformity ratio is, however, found acceptable in practical installations, and so also is the latter when the values of illumination are high. It may therefore be concluded that lighting units having these polar curves could be employed in large systems at values of spacing/height ratio up to 34 % above that given by the formula $\sqrt{2}\tan\mu$, and in certain circumstances up to 46 % above this figure.

It is evident that a large latitude is permissible in the value of spacing/height ratio at which these light distributions can be used in extensive systems, which is a satisfactory condition from the practical point of view.

(5) APPLICATION IN SMALL LIGHTING SYSTEMS

In Fig. 11 let PP_1 represent the elevation of a circular plane having a lighting unit suspended at O above its centre S. In order that the illumination at P and P_1 should be a maximum the angle POS should be the dispersive angle of the lighting unit. In Fig. 11 it is 46° 30′, the dispersive angle of the steel reflector fitting standardized in B.S.S. No. 232—1935. The polar curve of this fitting is shown dotted at O.* Superimposed on this is shown in full lines the optimum polar curve having the same dispersive angle and the same quantity of luminous flux. The contour curves corresponding to these two polar curves are shown in dotted and full lines respectively on PP_1 as a base-line below. It will be seen that the illumination on the plane due to the optimum light distribution is more nearly uniform than that due to the British Standard reflector. In the former case the ratio of minimum to maximum illumination is 0·395 and in the latter case it is 0·23. The average illumination on the plane also is higher in the former case as the optimum light distribution emits 65·4 % of its flux below the dispersive angle, as against 60 % emitted by the British Standard reflector. This illustrates the fact that in small installations the optimum light distribution would usually give more uniform illumination than a practical light distribution under similar conditions.

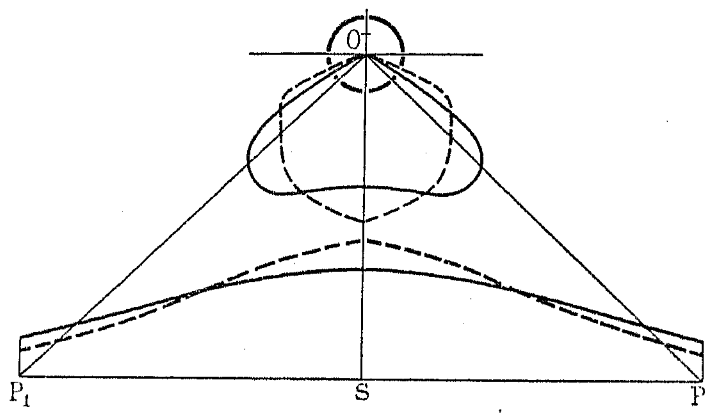


Fig. 11

---

* This curve is reproduced by permission of the Controller of H.M. Stationery Office. It is taken from Technical Paper No. 3 of the Department of Scientific and Industrial Research, entitled " Light Distribution from Industrial Reflector Fitting No. 1 (British Engineering Standard)."

In the case of the optimum light distribution, however, it is necessary to investigate how the illumination at P will vary as the lighting unit at O is raised or lowered vertically. If θ is the general symbol for the angle POS, μ being the particular value when this angle is the dispersive angle, it is convenient to plot the illumination at P against the ratio $\tan\theta/\tan\mu$. The curve so obtained is then applicable to any optimum light distribution and it is shown in full line in Fig. 12, in which the illumination at P is assumed to be unity when $\theta = \mu$.

From this curve it can be seen that the illumination at P is 70 % of the maximum value, or greater when $\tan\theta/\tan\mu$ is between the limits 0·63 and 1·44. Therefore in the case of four lighting units at the corners of a square of fixed size the spacing/height ratio may be varied between 63 % and 144 % of the value given by the formula $\sqrt{2}\tan\mu$ without the illumination at the centre of the square falling below 70 % of its maximum value. The latitude allowable in the value of spacing/height ratio in small lighting systems is thus sufficiently great for practical purposes.

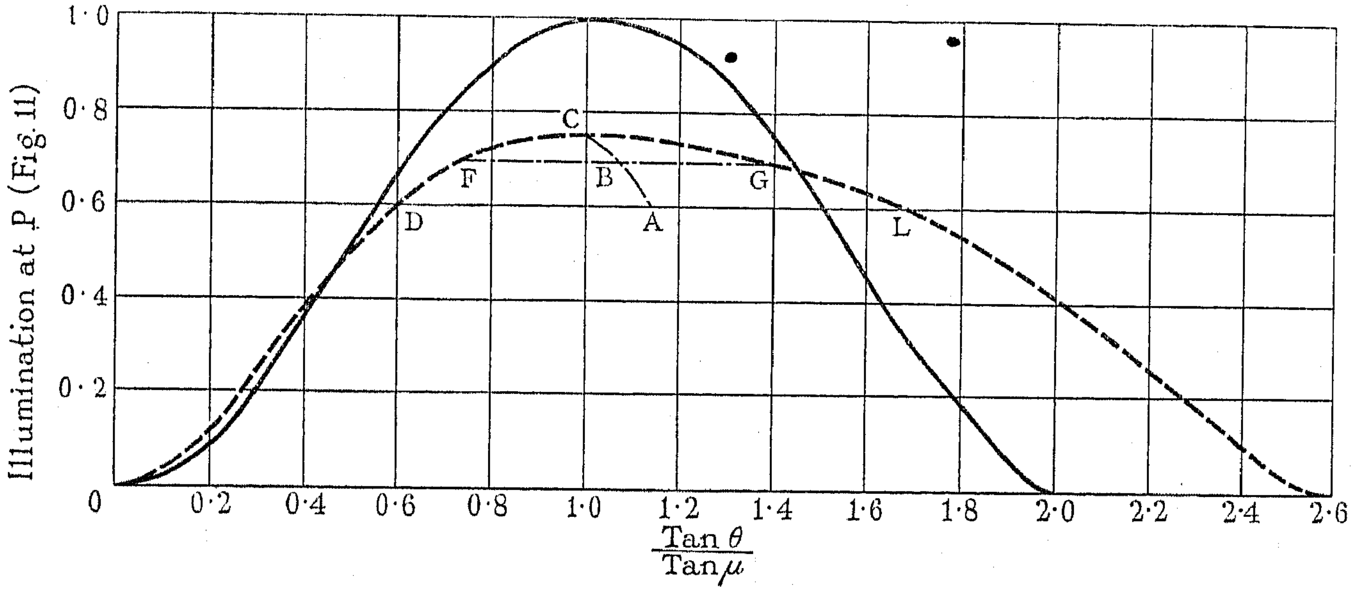


Fig. 12

The variation of the illumination at P due to the British Standard reflector fitting is shown by the dotted curve in Fig. 12. It falls away from its maximum value as the height of the lighting unit is varied more slowly than that due to the optimum light distribution. This, however, is compensated by the fact that the maximum illumination at P due to the British Standard reflector fitting is only 75·7 % of that due to the optimum light distribution.

(6) THE TESTING OF LIGHTING FITTINGS

In his previous paper* the author pointed out that the dispersive angle might be found experimentally. The method suggested was to suspend the lighting unit under test as at O (Fig. 11), place a portable photometer at P with its registering surface horizontal and facing upwards, and then raise or lower the lighting unit until the photometer showed maximum illumination. The angle POS would then be the dispersive angle.

In practice it would be found necessary to plot values of E, the illumination at P, against some function of the height of the lighting unit, and if it was plotted against $\tan\theta$ (θ = angle POS) curves similar to those in Fig. 12 would be obtained. The horizontal axis would be scaled in numerical values of $\tan\theta$, but this would make no difference to the shape of the curves.

In Fig. 12 the point at which E is a maximum is more sharply defined in the case of the optimum light distribution than in the case of the British Standard reflector. To avoid any difficulty which might arise in determining this point in cases in which it is not sharply defined, it would be convenient to draw a curve such as ABC in Fig. 12. This curve is such that it bisects the horizontal chords of the curve of which the maximum point is required; e.g. A is the mid point of DL, B of FG, etc. When produced this curve should pass through the maximum point as it does at C. Determined in this way there need be no ambiguity about the value of the dispersive angle. If the dispersive angle is not sharply defined it is an advantage in one respect, as it permits the spacing/height ratio to be varied more widely from the value $\sqrt{2}\tan\mu$ without noticeably decreasing the illumination on the plane. The dispersive angle of the British Standard reflector is thought to be less sharply defined than that of most practical lighting units.

The curves in Fig. 12 may also be found experimentally without raising and lowering the lighting unit. If the distance SP in Fig. 11 is l, the illumination E registered by the portable photometer at P would be given by

$$E = \frac{I}{l^2}\sin^2\theta\cos\theta$$

where θ is the angle POS and I is the luminous intensity of the lighting unit at this angle. When the lighting unit is raised and lowered l is constant, so that the photometer readings are proportional to $I\sin^2\theta\cos\theta$. If the lighting unit were stationary and the value of l varied by moving the photometer horizontally along PP_1 the photometer readings multiplied by l^2 would be proportional to $I\sin^2\theta\cos\theta$ and $\tan\theta$ would be proportional to l. Hence the curves in Fig. 12 may be produced in practice with the lighting unit stationary, by plotting El^2 to a base of l. The tangent of the dispersive angle would then be found by dividing the value of l at which El^2 was a maximum, by the mounting height of the lighting unit.

---

* *Loc. cit.*

(7) COMPARISON OF OPTIMUM AND PRACTICAL POLAR CURVES

When a practical polar curve is compared with the optimum polar curve having the same dispersive angle, it is usually found that the latter has a lower value for the ratio $I_0/(I_\mu \cos^3 \mu)$, where I_0 and I_μ are the values of luminous intensity vertically downwards and at the dispersive angle, respectively. The value of this ratio in all the optimum curves is about 2·5, it being the ratio between the illumination at S and that at P (Figs 1A and 11). In practical polar curves this ratio may lie between 4 and 6. The lower value of this ratio in the optimum polar curves seems to be the inevitable consequence of the fact that they produce uniform illumination, as those practical polar curves having a high value for this ratio produce unduly high illumination vertically below the lighting units in large systems. The author has suggested* that this ratio might be used as a criterion applicable to practical light distributions and indicating their suitability or otherwise for producing uniform illumination. This ratio can easily be found experimentally.

The optimum polar curves also usually have a larger angle of cut-off than a practical polar curve with the same dispersive angle. The advantages of a large angle of cut-off are a reduction in the number of lighting units required to produce the full value of illumination at a local part of the plane in a large system, and a reduction in glare.

The first advantage may be illustrated by reference to Fig. 1. If the lighting units depicted there had optimum light distributions and were suspended at the appropriate value of spacing/height ratio, it would only be necessary to switch on those marked L_1 to L_4 inclusive to produce the full value of illumination at P. If, however, the British Standard reflector were used, L_1 to L_{12} inclusive would be required for this purpose.

The disadvantages of a large angle of cut-off, apart from any loss in luminous efficiency involved, are that it may make it undesirable to suspend the lighting units at less than a certain mounting height, and that the shadows cast on the plane by a body projecting above it would be slightly deeper in intensity.

With regard to the first disadvantage the point is that a person walking about under the lighting units should not be liable to get into positions where his head was not in the direct light from the lighting units, as in these circumstances it might become difficult to recognize him. In the system shown in Fig. 1, the position where this would be liable to occur, if it occurred at all, would be P. Assuming that optimum light distributions at the appropriate value of spacing/height ratio are used, the condition that must hold to prevent this occurring is that the lighting units must be at least as far, vertically, above the person's head as the latter is above the plane. A consideration of the information previously given regarding the angle of cut-off will make this readily apparent. Taking practical figures, if the plane is 3 ft. above the floor-level and the person 6 ft. high, the minimum height of the lighting units above the floor should be 9 ft. Hence lighting units intended for suspension at this height or less should have a smaller angle of cut-off than that in the optimum polar curves. It so happens, however, that a reduction in the angle of cut-off in these curves entails only a small sacrifice of the uniformity ratio on the plane; for example a reduction of the angle of cut-off in Fig. 6 from 25° 14′ to 20° caused the uniformity ratio on the plane to fall only 5 %, i.e. to 95 %. This modification therefore presents no difficulty and it would be confined to low-power lighting units as it is only such that are suspended at a height of 9 ft. or less above the floor.

It is difficult to assess the importance or otherwise of the second disadvantage of a large angle of cut-off mentioned above. The increase in the depth of shadows is attributed to the reduction in the number of lighting units contributing to the illumination at any one point in the plane. The number contributing to each of the test points in Fig. 1 would be as follows:—at L_1, 5; E, 7; F, 7; G, 7; H, 6; K, 6; M, 6; N, 4; P, 4; Q, 4; R, 6; S, 6; T, 7. Each test point is not far from the centre of its respective group of lighting units. As the number of these is never less than four the shadows cannot be much more troublesome than those produced by a body at the centre of four lighting units arranged in a square. This is not a very unfavourable condition, and where the lighting units are suspended at 9 ft. or less above the floor it would be ameliorated in any case because it has been found advisable to reduce the angle of cut-off in these for another reason. It is possible, however, that lighting units of moderate power for suspension at a height slightly greater than 9 ft. above the ground might also with advantage have the angle of cut-off slightly reduced. In the case of high-power lighting units, however, say of 500 watts or over, it seems best not to reduce it at all. The reasons for this are, that an installation of high-power lighting units would have to be very extensive and singularly free from obstructions for many of the lighting units to contribute to the illumination at one part of the plane, and the two advantages of a large angle of cut-off, given above, would be particularly applicable to high-power lighting units.

The two disadvantages of a high angle of cut-off, given above, would not apply to totally indirect-lighting units, which have only to illuminate a white ceiling; neither would they apply to lighting units for exterior installations, as in public squares, etc., as these are always mounted high, and the increase in depth of shadows would not be of any moment.

It appears, therefore, that when the only requirement to be met is that the illumination on the horizontal plane should be uniform, the optimum light distributions may be considered to be the most suitable in exterior installations as in public squares, in totally indirect interior installations, and in direct interior installations in which high-power lighting units are used. For direct interior installations of medium- or low-power lighting units, similar light distributions with a slight reduction in the angle of cut-off would be most suitable.

---

* *Loc. cit.*

It would be a mistake, however, to assess the performance of a practical lighting unit entirely by the extent to which its light distribution agreed with one of the optimum light distributions described here. A high luminous efficiency is often of more importance than the shape of the polar curve, and in many practical cases it would no doubt be better to sacrifice the latter consideration to the former, if they cannot be obtained together. Also, practical lighting units often have to fulfil other requirements besides that of producing uniform illumination on the horizontal plane. It is frequently necessary to illuminate the walls of a room in interior installations or of a building in exterior installations. Sometimes fittings for interior installations are required to illuminate both floor and walls and throw sufficient light on the ceiling to bring out architectural features or to relieve the gloomy appearance of a dark ceiling. The opinion is held by some that perfect uniformity of illumination is undesirable as it induces a feeling of depression. Thus the greatest care is necessary in drawing conclusions from the comparison of a practical light distribution with those described here, and particular attention should be paid to the question of luminous efficiency.

The use of the term " optimum " in connection with the light distributions described here is justified only under certain conditions, as they are not the best that could be used in every circumstance. It was found necessary, however, to employ some designation for them, and the alternatives available did not commend themselves so much as that used.

DISCUSSION ON "A REVIEW OF RECENT DEVELOPMENTS IN RURAL ELECTRIFICATION"*

WESTERN CENTRE, AT EXETER, 22ND FEBRUARY, 1937

Mr. H. F. G. Woods: The price at which electricity is being offered to consumers in Dumfriesshire appears to be particularly low, having regard to the thinly populated and mainly agricultural character of the area. It is no doubt largely due to so favourable a price, coupled with the author's own initiative, that the remarkable development of the area is to be attributed.

In his introductory remarks the author made no reference to the financial results of the operation of the undertaking, and from the figures which have been given relating to the number of consumers and their average consumption I should be surprised to learn that the undertaking is yet self-supporting. It would, I think, be of general interest if he would give a statement of the total sales of energy in the last financial year with the corresponding figures of gross and net revenue, and also of the ratio of operating expenses to gross revenue.

The second point to which I would refer is the use of earth-leakage circuit-breakers for the protection of consumers' installations. Circuit breakers of this type are comparatively delicate pieces of apparatus, and are liable to get out of order. Although failures are not to be expected to be of frequent occurrence they are bound to happen sometimes, and even if the chance of failure is as low as 1 in 1 000 the effect is that one consumer in every thousand is exposed to the very risks which circuit breakers are installed to prevent. The quick disconnection from the system of any apparatus which may develop a fault to earth is a matter of primary importance to all undertakers who operate in rural areas. For achieving maximum security in this respect I suggest that the alternative system of multiple earthing promises to be not only more effective but also less costly and more reliable. I think it would be generally helpful if the author would state the reasons which induced him to install earth-leakage circuit-breakers rather than to adopt a system of multiple earthing with neutral conductors connected to earth through earth electrodes at sufficiently frequent intervals, with an earth-continuity conductor installed on each consumer's premises to connect the frames of all appliances together and to the neutral conductor of the system as well as to a local earth.

Mr. T. H. Rogers: I find no mention in the paper of means for regulation of voltage. On rural schemes where one has to tap 11-kV lines for each farm and to tap 33-kV lines at intervals of, say, 5 miles, it is difficult, with the small revenue available, to justify voltage-regulator equipment. I should like to ask the author whether any such means has been found necessary and what system, if any, has been adopted.

Mr. J. Dempsey: In Dumfriesshire the author was faced with the problem of providing, on a sound financial basis, supplies of electricity to a rural population of approximately 62 000 scattered over an area of 1 060 square miles. To appreciate his achievement fully it must be remembered that the average density of population of the rural areas of Great Britain is approximately 130 persons per square mile. The fact that the author has managed to sell to the extent of 1 000 units per consumer per annum should act as an incentive to the supply industry as a whole.

In regard to overhead-line distribution in rural areas generally, it would appear that extreme simplicity and cheapness in layout, such equipment and layout being suitable for future standard expansion, is essential in the first instance, to ensure a suitable return on capital expenditure, at least by the end of the fourth year of working. As the author's system has now been operating for approximately that period of time, I should be glad to know what return is being shown against his capital expenditure.

---

* Paper by Mr. D. Ross (see vol. 77, p. 797).

Nowadays most towns are encircled by a cable system of e.h.t. ring mains, generally laid in the fringe areas or thereabouts, and it is suggested that the overhead-line rural distribution should start from one of the substations of such a ring-main system, and return in the form of a rural ring main, after having served the most suitable load points, to another substation of the same ring main or system. This arrangement could be repeated throughout the rural perimeter, and the rural lines themselves could be paralleled where such demands called for development. The following advantages would appear to accrue: (1) Shortest runs of rural overhead lines, covering only the areas they are intended to serve, namely the rural areas. (2) Employment of step-up transformers initially avoided. (3) Reduced voltage-drop owing to the cable ring main and overhead-line ring-main system being supplied from both ends, and avoidance thereby initially of voltage-regulating equipment. (4) Two-way supplies available at each terminus of the rural ring mains, where these are tapped from the substations of the cable ring mains, these supplies being controlled by the more elaborate and selective protective gear which it is generally more economically possible to fit on cable systems. (5) Reduced short-circuit kVA available on the rural lines, owing to remoteness from main source of supply; hence less expensive switchgear and more selective operation of relays and fusegear. In addition, reflections from the overhead lines, due to atmospheric conditions, etc., are damped out in the underground cables before striking the main source of supply. (6) All-round switching flexibility for repairs and maintenance.

The advantages of the more homogeneous copper-clad steel conductor are advocated, especially for the smaller sizes of lines, and I should be glad to have the author's remarks on this. Reference is made to the apparently successful method adopted in certain areas of running the main 3-phase lines with one conductor earthed. A material saving in insulator costs, and reduction of outages, is claimed for this method, but it necessitates a step-up transformer in the first instance.

I consider that the author is taking a step in the right direction in the general use of earth-leakage circuit-breakers, in view of the high earth resistances very often obtained in rural areas. The results obtained from efforts to reduce this resistance by the application of various salts and electrolytes around the electrode are unsatisfactory and of a temporary nature. I should be glad to know whether the author has experienced any troubles in the working of the circuit breakers he has installed.

Mr. D. R. Beckett: I note that in localities where earthing involves difficulties the author uses earth-leakage circuit-breakers for the earthing of the transformer neutral points, in addition to their use on consumer's premises, and that he states that satisfactory discrimination is obtained. I should like to know what setting he has found most satisfactory for the earth-leakage circuit-breakers at the transformers in order to obtain this discrimination.

Mr. J. W. Spark: I am agreeably surprised at the sales achieved with the tariff adopted, which no doubt is low for this class of supply. Good salesmanship and service on the part of the author's undertaking are very evident.

The author described a low-priced cable suitable for rural work; I have never understood why any cable at an attractive price which gives satisfactory results in rural areas should not give satisfaction in urban areas. I quite appreciate that longer untapped lengths are used in rural supplies and that voltage-drops have to be contended with, but similar problems in relation to voltage have to be contended with on any system. I should like more information on the subject.

Regarding the author's remark that "H" poles are generally not necessary, I should like to ask whether in many cases the job could not be done more satisfactorily with "H" poles instead of with the wood poles reinforced with steel supports shown on the screen.

Mr. G. C. R. Ridge: Although the 3-phase 4-wire system is slightly more costly, this disadvantage is more than compensated for by the fact that it will transmit considerably more energy than the single-phase 3-wire system. This is an important factor which does not appear in the comparison given in the paper, and I should be glad of the author's comments upon it.

Mr. C. C. Hodges: I am not in favour of the method of fusing 11 000-volt spur lines at the teeing-off point with no further protection or isolation at the transformer. Do not the Electricity Supply Regulations require that there shall be a means of isolation always within sight of an operation on the transformer?

Mr. E. W. Faithfull: I am particularly interested in the section of the paper dealing with earthing, and I agree that it is impossible to obtain a satisfactory earth in districts without a public water supply. The usual method of employing an earth plate, or a large-diameter pipe buried or driven in the ground, is far from satisfactory, as the resistance to earth will vary with the nature and state of dampness of the soil, and even under good conditions a low resistance is unobtainable. The author advocates the use of earth-leakage circuit-breakers to overcome this difficulty. In these circuit breakers a very fine-wire coil is used to actuate the switch, and the only connection with earth that the apparatus to be protected can have is through this coil. I suggest that a danger exists that, in the event of the trip coil becoming burnt out or the connection being broken through any cause, the relay will not only fail to function but the apparatus to be protected will be entirely insulated from earth; and, if a fault then occurs, fatal results may follow. I appreciate that a test key is always provided and that the arrangement may be tested from time to time to ensure that the coil will operate, but even this is no proof that operation will be certain under fault conditions. I should like to know whether the author has experienced any trouble of this nature.

Mr. W. Roberts: In his statement justifying the use of single-phase rather than 3-phase motors for farm equipment, the author only deals with first cost, but when making out a case for small transformers fully loaded as against larger transformers lightly loaded he adds running costs over a year at the very high figure of 2d. per unit. I suggest that if the question of single-phase motors is dealt with on the same lines the bad efficiency and power factor of the single-phase equipments as compared with 3-phase machines will not allow him to arrive at the same conclusions. Admittedly this will not affect the undertaking, but surely the extensive recommendation of single-phase machines is going to hamper development. The other point that arises is that the undertaking pays the cheap part of the combined total, whereas the consumer presumably pays for the single-phase motors, i.e. the expensive portion of the combined total.

Mr. A. L. Keet: I admire the author's simple and neat method for fixing transformers to main-line transmission poles; these methods could be used with advantage in S.W. England instead of some of the more cumbersome arrangements at present in use.

It is interesting to record that in a typical village in the rural area of the Exeter Corporation where no gas supplies are available the conditions are as follows: Number of houses, 230; number of consumers, 219; average annual consumption per consumer, 950 units; average price per unit obtained, 1·6d.

I should be glad if the author would state the average price obtained per unit in Dumfriesshire.

It would be interesting to have details as to the cost of the neat e.h.t. fuse adopted by him. Has he experienced much trouble due to gales, and, if so, what has been the nature of the trouble which has arisen?

Mr. D. Ross (*in reply*): In reply to Mr. Woods, I purposely omitted reference to the financial results of the undertaking with which I am engaged as these will be the subject of another paper. I would, however, refer Mr. Woods to the Electricity Commissioners' Return of Engineering and Financial Statistics, which I think will give the desired information. I should like to confirm, however, that the undertaking is self-supporting.

With regard to the adoption of earth-leakage protection in preference to multiple earthing, this was only agreed upon after careful consideration, not only of the initial cost but also of the performance under actual working conditions, and 3 years' experience has fully justified the choice. Whilst it is admitted that any piece of mechanism may become sluggish and get out of order, the conditions are no worse than in the present system of earthing, where an earth connection can become disconnected. Moreover, there is no doubt that with more experience and further experiments an improved earth-leakage breaker can be produced which will give 100 per cent protection, and I have actually examined and tested a new design without toggle mechanism which should overcome the present objections to this method of protection. The multiple earthing system would only be efficacious on a developed network, as at the initial stage few earth plates would be installed at consumers' premises, with the result that the earthing of the neutral beyond a "break" would be doubtful. Moreover, should the substation "earth" resistance be high (which is very likely) a "break" would obviously cause a rise of voltage on the neutral on the substation side of the "break." The protection afforded by this method is, therefore, very problematical, and will depend on the care exercised in establishing low-resistance earth plates along the route of distribution. The cost of installing additional earth plates could easily exceed that of earth-leakage protection, whereas, excepting the substation earth-leakage circuit breaker, with "all insulated" installations the consumers' earth-leakage protection will only become necessary as cooking, heating, and power load, is connected.

Mr. Rogers raises the question of voltage regulation, and in reply I would state that the only regulation provided in the meantime is on the 33/11 kV stepdown transformers, which have automatic on-load tap-changing gear, and on very long 11-kV lines, where automatic booster transformers are installed. As the load develops and the losses and expense justify it, the 11-kV to 400-volt step-down transformers at the main distribution centres will also be provided with automatic on-load tap-changing gear. Mr. Rogers mentions the tapping of 33-kV lines at intervals of 5 miles: this arrangement does not appear justifiable on a rural distribution scheme with an extensive 11-kV distribution network. I would suggest that intervals not less than 10 miles would be more economical. Naturally the interval will depend on local conditions, and as I am not familiar with Mr. Rogers's area I am unable to give any definite views.

Replying to Mr. Dempsey, I would refer him to my reply to Mr. Woods regarding the financial results of the operation of the undertaking. I disagree with Mr. Dempsey's suggested arrangement for a rural distribution system. Whilst it might be applicable to a small rural area on the fringe of an urban distribution system, it would be quite impracticable in the case of an extensive area covering, say, 500 square miles, where the control of each feeder at some central point is desirable. Dealing in turn with the advantages claimed: (1) Would only apply in restricted areas and depends entirely on local conditions. (2) Would appear to have in mind 6·6-kV urban distribution, and as 11 kV is the voltage generally employed on rural distribution step-up transformers are not required. (3) This method can be equally applied to the usual system of combined radial and ring-main feeders. (4) The same advantages occur on the standard system (3). (5) This point is not appreciated, as the short-circuit kVA on rural lines is comparatively small and can readily be dealt with by the smallest standard sizes of switchgear manufactured. The operation of relays is rendered more selective by the simpler arrangement of feeders and interconnections on the standard system (3). The employment of underground cable at overhead-line terminations to damp out surges and lightning disturbances is not considered satisfactory, as not only is the effect uncertain but there is the risk of damaging the cable and also causing interruptions to supply on the underground system. (6) The same degree of switching flexibility is obtained on the standard system (3).

For the smaller sizes of line I maintain that steel conductor is more satisfactory and is less expensive than copper-clad steel conductor.

I refer Mr. Dempsey to my reply to Mr. Woods on the subject of earth-leakage breakers.

The information regarding the setting of substation earth-leakage breakers desired by Mr. Beckett is as follows: These breakers are equipped with a variable setting which must be adjusted according to the resistance of the leakage-circuit electrode and the main earth electrode. As these electrodes are in parallel the leakage current will divide between them in accordance with the resistance of each and with the impedance of the earth-leakage trip coil. The chief point is to ensure that the earth-leakage circuit electrode is not in the same zone as the main earth electrode, otherwise uncertain operation will result. The two electrodes should be spaced at least 15 ft. apart, and this distance should be increased should the resistivity of the soil be high.

Replying to Mr. Spark's question why any cable at an attractive price, which gives satisfactory results in rural areas, should not give the same satisfaction in urban areas, it will be appreciated that rural cables are designed rather on the basis of voltage-drop than on that of current-carrying capacity, so that the conductor temperature-rises involved are very small; this permits the use of smaller thicknesses of dielectric than are necessary in the usual underground cable used in urban areas, which are much shorter in length, are more heavily loaded, and may work with a maximum temperature-rise. In addition, the armouring has been eliminated on rural cables as these are less liable to mechanical damage.

The adoption of single wood poles throughout, even where reinforcement is necessary in the special case of supporting a 150-kVA transformer, is fully justified not only on the grounds of economy but also for simplicity and appearance.

Mr. Ridge suggests that the 3-phase 4-wire system is superior to the single-phase 3-wire system. Whilst this may be true for the larger distribution systems the reverse is the case for small systems in rural areas; weight of copper for weight of copper a single-phase 3-wire system will deal with a larger unbalanced load than a 3-phase 4-wire system. Moreover, the cost of other items such as h.t. line, fusegear, transformers, etc., is much less on the single-phase system.

Replying to Mr. Hodges, my experience of fusing 11-kV spur lines at tee-off points with no further protection at the transformers has proved this a most economical and satisfactory method, particularly when it is remembered that the cost of renewals during thunderstorms is considerable.

I do not think the Electricity Supply Regulations require that there shall be means of isolation within sight of pole-mounted transformers, although this provision is necessary for transformers in substations which come under the Factory and Workshop Acts.

Dealing with Mr. Faithfull's question, I should like to mention that, with the exception of one breaker, the coil of which was burnt out during a lightning storm, no electrical trouble has been experienced with approximately 800 earth-leakage breakers, and so far as open-circuits are concerned the conditions are the same as those obtaining on other electrical installations, any of which are liable to have the earth connections accidentally or wilfully interfered with.

Although I mentioned 2d. per unit when comparing sizes of small transformers, if Mr. Roberts cares to accept 1d. per unit the case is not materially affected. The figure of 2d. per unit was assumed because this is the average price per unit sold throughout the country.

The question of efficiency and power factor of single-phase motors was purposely omitted as it was considered that it did not substantially affect the comparison, the majority of motors used on farms only being operated for a few hours each week. The adoption of single-phase motors does not hamper development but has actually been proved to facilitate development by making supplies available at economic rates without recourse to guarantees and capital contributions.

Mr. Keet's figures giving the results of the electrification of a village in the Exeter Corporation rural area are very commendable, and provide another example of satisfactory rural electrification accomplished on the same economic lines as urban electricity distribution. The average price obtained per unit in Dumfriesshire for the year ending 1936 was 1·86d. The cost of 11-kV fuses, erected complete with steelwork and connections, is as follows: single-phase, £7 16s.; 3-phase, £10 17s.

Very little trouble due to gales has been experienced, as adequate clearance has always been provided between trees and the main lines. In the case of l.t. lines, however, as these must be erected along the roadside where trees cannot be disturbed, an appreciable amount of trouble is experienced. Lightning storms are the chief bugbear to overhead distribution systems, and will remain so until further investigation and research discovers a remedy.

NICKEL-IRON ALLOYS OF HIGH PERMEABILITY, WITH SPECIAL REFERENCE TO MUMETAL

By W. F. RANDALL, B.Sc.[*]

(*Paper first received* 29*th January, and in final form* 11*th August*, 1936; *read before the* METER AND INSTRUMENT SECTION 8*th January*, 1937.)

SUMMARY

The paper summarizes the development of high-permeability alloys from early researches to the commercial products of the present day.

The difficulties encountered during manufacture, and the precautions necessary in these metallurgical processes, are described.

Stress is laid on the correct methods of application to ensure that the magnetic properties of the alloys are utilized to full advantage, and the need for heat treatment is emphasized. Propositions are put forward to explain the mechanism of this heat-treatment process, and the practical procedure is given.

Data on curves show the electrical and magnetic properties of the alloys.

The paper finally discusses the practical applications of high-permeability materials, giving examples of commercial instruments and indicating cases in which their extended use would be advantageous.

(1) HISTORICAL INTRODUCTION

Alloys with magnetic permeabilities of six figures are so much a commonplace at the present time that it is somewhat surprising to recall how short is the history of such materials. They have found considerable and varied applications in the electrical industry.

Their development is bound up with investigations into the properties of nickel-iron alloys, and the beginnings of this research date from 1900, when Barrett, Brown, and Hadfield,[*] in the course of researches into the magnetic properties of steels, recorded that nickel-iron alloys were extremely permeable compared with other materials then available. The fact was merely recorded as of passing interest, as the saturation induction was low, and there was no development at the time—largely owing to the elementary nature of metallurgical technique. Apart from further work by Panebianco,[†] in 1910, nothing was done until the increasing demand for telegraphic facilities led to further examination of the propositions of Krarup,[‡] with a more exact examination into the magnetic properties of materials. There then arose a demand for a ductile metal with high magnetic permeability in fields of the small magnitude encountered in submarine telegraph-cable working, and the nickel-iron alloy subsequently named "permalloy," containing about 80 per cent nickel and 20 per cent iron, was discovered in the course of investigations carried out by Arnold and Elmen,[§] of the Bell Telephone Laboratories. Yensen,[||] during a series of researches into alloys with low watt loss, investigated the whole range of nickel-iron alloys and came to the conclusion that the highest permeability was obtained from a 50/50 alloy. The difference between his decision and that of Arnold and Elmen was due to his imperfect appreciation of the value of heat treatment. It is interesting to note, however, that some points obtained on his permeability curve, which were apparently ignored as untrustworthy, indicate the permalloy range.

The need for accurate control of composition and "purity" was emphasized by both investigations, but Arnold and Elmen made a most important advance by appreciating and stressing the essential need for correct heat-treatment conditions. Development work showed that these pure nickel-iron alloys had inherent disadvantages, and further efforts to overcome them were made by many investigators not only in America but also in Germany and in this country. These investigations are still proceeding.

(2) COMMERCIAL DEVELOPMENT OF HIGH-PERMEABILITY ALLOYS

In America, permalloy A, containing exactly $78\frac{1}{2}$ per cent nickel and $21\frac{1}{2}$ per cent iron, was displaced by permalloy C. In Germany, Gumlich evolved "megaperm," and in this country "mumetal" was developed and patented in 1925. All these alloys sacrificed the potential extremely high permeability of the selected nickel-iron composition for a lower figure which could be attained with much more certainty and without strict laboratory control.

These developments, it should be noted, were primarily undertaken to discover an alloy of stable properties adapted to the Krarup loading of submarine telegraph cables. The straightforward nickel-iron alloy, although having excellent permeability in its optimum condition, was difficult to control. Small variations in composition had a great effect upon magnetic properties, the heat treatment was complex, and the electrical resistivity was rather low. For the application proposed, it was necessary that the alloy should have perfectly stable characteristics—alteration when at a depth of 2 000 fathoms would be a serious matter and incur great expense—and consistent properties. The initial permeability should be as high as possible in order to obtain the greatest possible inductance with a minimum of material, and the resistivity should also be high to restrict electrical losses. Subsequently it became evident that ability to conform with these conditions implied that the metal was admirably suited for other commercial purposes.

---

[*] *Proceedings of the Royal Dublin Society*, 1900, vol. 7, p. 113; *Journal I.E.E.*, 1902, vol. 31, p. 674.

[†] *Rendiconti della R. Accademia delle scienze fisiche-matematiche, Napoli*, 1910, vol. 16, p. 216.

[‡] *Elektrotechnische Zeitschrift*, 1902, vol. 23, p. 344.

[§] *Journal of the Franklin Institute*, 1923, vol. 195, p. 624.

[||] *Transactions of the American I.E.E.*, 1920, vol. 39, p. 791.

Earlier work had shown the necessity for "purity" when seeking a high-permeability material. "Purity" is a rather loose term, but in this case it implied as close an approximation as possible to 100 per cent essential constituents with freedom from that small proportion of carbon, oxygen, and sulphur, which is generally connected with metallurgical products. Progress was greatly facilitated, therefore, if not actually made possible, by the use of the high-frequency electric furnace patented at that time by Northrup.*

The developments were separate but followed a somewhat parallel course. The effect of small foreign additions on the electrical resistivity of pure metals or alloys is known, and it is a general rule in metallurgy that increased complexity in the composition of alloys results in increased electrical resistivity, providing the additions made can be taken up by the existing metal to form a "solid solution." As increased electrical resistivity was one of the desiderata, investigators found other metals which could be taken up by the nickel-iron "matrix" without the separation of another "phase," giving this requirement. It was then a short step to adjust the proportion of this addition so that the best magnetic properties were obtained from the conglomerate. Manganese, molybdenum, chromium, and tungsten, were some of the metals successfully applied, permalloy C and megaperm being typical developments of this class.

The difficulties encountered with the control of the 80/20 nickel iron made it apparent that reliability and reproducibility were essential attributes of any alloy which was to be a commercial success, and the composition of mumetal was based on these considerations.

The line of argument followed in this case, which led to the addition of copper as an essential ingredient, was as follows.

The permeability of nickel-iron alloys is reduced greatly by strain. Internal strains tend to be greater with a hard, strong, alloy than with a softer and more easily deformable structure. It was argued that the addition of a cognate element would, without undue distortion, relieve the "stiffness" of the nickel-iron structure and achieve greater stability in this respect. This might be accomplished by adding to the nickel-iron basis an element with similar lattice dimensions, and it was found after many disappointments that, by a small adjustment of the nickel-iron ratio, an addition of copper acted according to anticipation.

(3) MANUFACTURE OF STRIP

A few words on this subject will illustrate the difficulties met with by the metallurgist in endeavouring to meet the requirements of the electrical engineer.

As the author is concerned with the manufacture of mumetal, the operations described are the most advantageous in respect of that material, but investigations have shown that the same principles apply generally to the whole range of high-permeability alloys based on nickel and iron.

It has been indicated already that accuracy of composition is essential for consistent magnetic characteristics, and, although there is a wider permissible range of variability in the complex high-permeability alloys, a small variation on either side of the optimum results in diminished permeability. To ensure the correct composition, knowledge of the proportionate losses of each element under the melting conditions employed is demanded, which can only be obtained by experience. Then, in addition to control of what may be termed the major composition, precautions must be taken to ensure that adventitious impurities do not enter into the melt in quantities sufficient to influence the properties. The source of such impurities may be (*a*) the raw materials employed, (*b*) the refractory container, or (*c*) external contamination.

With regard to (*a*), one is restricted by the purity of commercial supplies, but fortunately all the elements entering into the composition can generally be obtained in a condition approaching 100 per cent purity. The most suitable refractory is determined by experience, an essential characteristic being that it shall contain no deleterious compounds which can be reduced to the

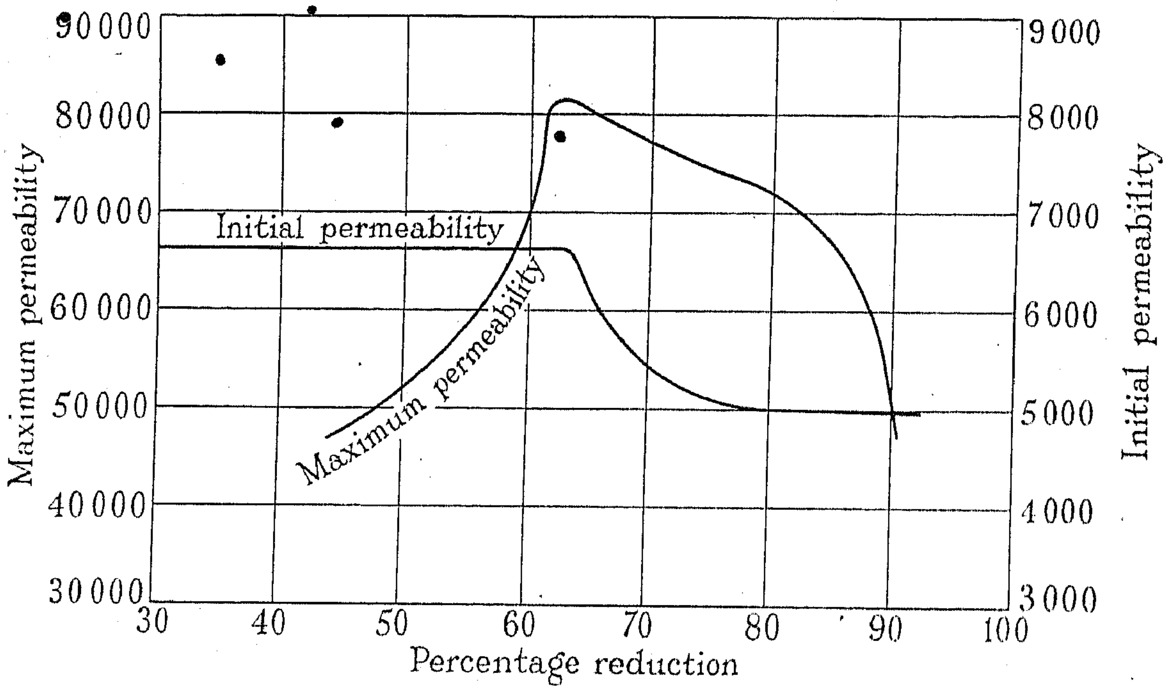


Fig. 1.—Mumetal strip: effect of rolling prior to heat treatment.

---

* *Transactions of the American Electrochemical Society*, 1921, vol. 39, p. 331.

elemental state and enter into the melt. Slag inclusions must of course be avoided, but these are of secondary importance from the magnetic point of view.

By the use of a high-frequency electric furnace contamination resulting from fuels is avoided, although the absorption of atmospheric gases cannot be prevented. Suitable covering slags reduce this to a minimum, and traces absorbed can be rendered harmless by treatment with non-detrimental deoxidants and slags. The rolling and drawing qualities of the cast metal are largely determined by the nature of this process, and one of the difficulties in the manufacture of mumetal is in striking a balance between adequate working qualities on the one hand and high-grade magnetic characteristics on the other. The best results, both mechanical and magnetic, are obtained from metal which is protected, not only in melting but also throughout the hot rolling, annealing, and heat-treatment processes, from penetration by oxidizing, sulphurous, or carbonaceous gases. To achieve this, electric forging and preheating furnaces are desirable, but as these are not at present available for commercial production the next best procedure—muffle protection—is employed. When contact cannot be economically avoided, subsequent reheating in a hydrogen atmosphere may be resorted to, to remove the undesirable impurities which have been collected during the earlier operations.

The stabilization of properties is very dependent upon the manner of working down to strip. The result of cold working to different extents, shown in Fig. 1, is rather surprising. The abscissae represent the percentage reduction to which the finished strip has been subjected prior to final heat-treatment, and it will be seen that the permeability obtainable varies according to the degree of the cold work. Moreover, the working for highest initial permeability is not identical with that for maximum permeability.

It should be emphasized that these curves refer to working carried out on the metal in the cold state; and that hot working, carried out at temperatures at which the metal is, in effect, self-annealing, has no similar effect. This latter process is, however, more economical when heavy sections are being made, and for this purpose it must be utilized in practice, but it is discontinued when the thickness of the strip or sheet is about 3 times the finished thickness required. From that stage, further reduction proceeds by cold working in accordance with the curves. Unless these conditions are observed the metal will not respond readily, if at all, to standard annealing processes.

(4) EXPERIMENTAL DEVELOPMENT OF HIGH-PERMEABILITY MATERIALS

(a) Theoretical

In common with other magnetic materials, nickel-iron alloys require annealing to develop full magnetic permeability, but they are more sensitive to variations in this process than transformer irons or dynamo sheet. Although many theories have been put forward, the mechanism of the operation has not yet been fully explained. The magnetic properties resulting from heat treatment are known to be affected by the orientation of the crystals in the alloy, and by unequal cooling rates between different parts of the same piece. For the latter reason it is always more difficult to develop high permeability in thick, heavy sections than in light thin sections.

It has been suggested that satisfactory results depend upon the following factors:—

(i) *The retention at air temperatures of an alloy structure normally stable only at high temperatures.*—This view has been supported by the fact that the high magnetic permeabilities are obtained by rapid cooling from a temperature between 900° and 1 000° C., a process which would tend to conserve the atomic configuration existing at that temperature. This theory presents difficulties, as the structure is non-magnetic over the high temperatures at which it is presumed to be stable. On this hypothesis subsequent reheating to a lower temperature would remove the mechanical strains consequent upon the quenching operation without any considerable effect upon the molecular structure. No evidence to support this view can, however, be obtained by examination either with the microscope or with X-rays.

(ii) *The influence of a phase or constituent of the alloy with a markedly different solubility over the lower temperature-range.*—This theory attaches importance to the "impurities" present in the metal, and this fact lends colour to it.

These statements may require more elucidation. Metals or alloys in the solid state are capable of absorbing or "dissolving" other metals, or even non-metallic compounds. The extent of this ability depends upon the nature of the original alloy and the metal or compound with which it is in contact. As in the case of liquid solutions, the "solubility" will vary with temperature, and may increase or decrease as the temperature rises. A constituent may be dissolved at high temperatures and out of solution at low temperatures, in which case it will be precipitated by cooling the alloy slowly. Rapid cooling, on the other hand, may inhibit the proper separation of such a "phase" which is, as it were, retained forcibly by the dissolving medium. Such a process results in a modification of internal conditions, which would be expected to have its effect upon magnetic properties even though the total constituent proportion of the "phase" retained in solution, or vice versa, is minute. The very considerable modification of magnetic properties obtained by dispersed precipitation of relatively minute proportions of a phase less soluble at lower temperatures is exemplified by the "isoperm" type of alloy with constant permeability characteristics, which, although not classified as a high-permeability alloy, is closely allied in composition to those under consideration. There is no doubt that the solution or precipitation of the small proportion of oxide or carbide present in these alloys has a profound effect upon the magnetic characteristics.

It is probable, however, that this is merely a specialized case of the more general hypothesis given in (iv) below; that is to say, the precipitation or solution is not primarily of importance *per se*, but only so far as it affects the internal stresses.

(iii) *The degree of order remanent in the space lattice at air temperature.*—It appears evident that this must affect the magnetic characteristics, and the degree of "ordering" is influenced by the form of heat-treatment adopted. Evidence that this has some bearing on the results is obtained from the fact that the electrical resistivity varies with the magnetic condition, maximum magnetic softness and maximum electrical resistivity being concomitant. It is known that the electrical resistance of alloys varies with the degree of "order" in the space lattice. It is difficult to explain some of the vagaries of the alloy, however, if this is regarded as a major factor.

(iv) *Elimination of internal strain.*—It is well known that ferromagnetic materials alter in length when magnetized, the alteration being either positive or negative and varying with the intensity of magnetization. At low magnetic inductions the magnetic metals nickel and iron are opposite in regard to this magnetostriction characteristic; that is to say, the one contracts in length while the other expands. An intermediate alloy of the two metals exhibits zero magnetostriction; and, while the exact composition is dependent on the strength of field employed, the range lies very near the original permalloy A composition. Metal through which a magnetic flux is passing is therefore in a state of molecular strain, and this theory demands the equalization of these magnetostrictive stresses by opposite mechanical stresses applied to or introduced into the metal. A non-isotropic material brought from an elevated temperature cannot be cooled slowly and equally enough to ensure an identical rate of loss of heat from all parts, and in practice local strains are bound to occur, although the magnitude may be very small.

This mechanical strain may be increased by rapid or unequal cooling, while magnetostrictive strain is a fixed characteristic of any given alloy, varying in a definite manner with the magnetic field. A condition is therefore conceivable in which the metal has been produced with a degree of residual mechanical stress such that, when magnetization occurs, the opposing magnetostrictive stresses set up are equivalent in magnitude but opposed in direction. Such an ideal condition is not practically obtainable, but residual strain may be varied to some extent and there are indications, for example, that when alloys of greater magnetostriction than normal "mumetal" are cooled at a greater rate than is usual, better results are given than with the normal treatment. It is noteworthy that the nickel-iron alloy with zero magnetostriction in small fields is not the alloy of declared highest magnetic permeability; and this is in accordance with the theory, for the most careful and prolonged cooling process cannot give a metal absolutely free of stress, and we must assume that there is residual mechanical strain in this alloy even with the best possible heat-treatment. It is simpler to adopt a heat-treatment which leaves behind a determined residual stress than to neutralize those stresses consequent upon magnetostriction. Supporting evidence for this point of view is obtained from the fact that alloys with negative magnetostriction, i.e. richer in nickel, increase in permeability when subjected to small tensile strain, while those with positive magnetostriction diminish under the same conditions. The diminution of permeability in these alloys consequent upon distortion is also in keeping with this hypothesis, as is the considerably improved permeability obtained by applying a magnetic field during the cooling operation.*

(v) *An optimum orientation of the crystals.*—The effect of this, and the manner in which it is accomplished by controlling working-down operations, have already been mentioned. The effect is to be expected, for metal crystals are not magnetically isotropic but are more easily magnetized in certain directions.

(b) Practical Heat-Treatment

There is evidence in support of each hypothesis, but the heat treatment of mumetal assumes the truth of (iv) and (v), and to some extent of (iii), which is probably connected with (v). The requirements for successful heat-treatment are:—

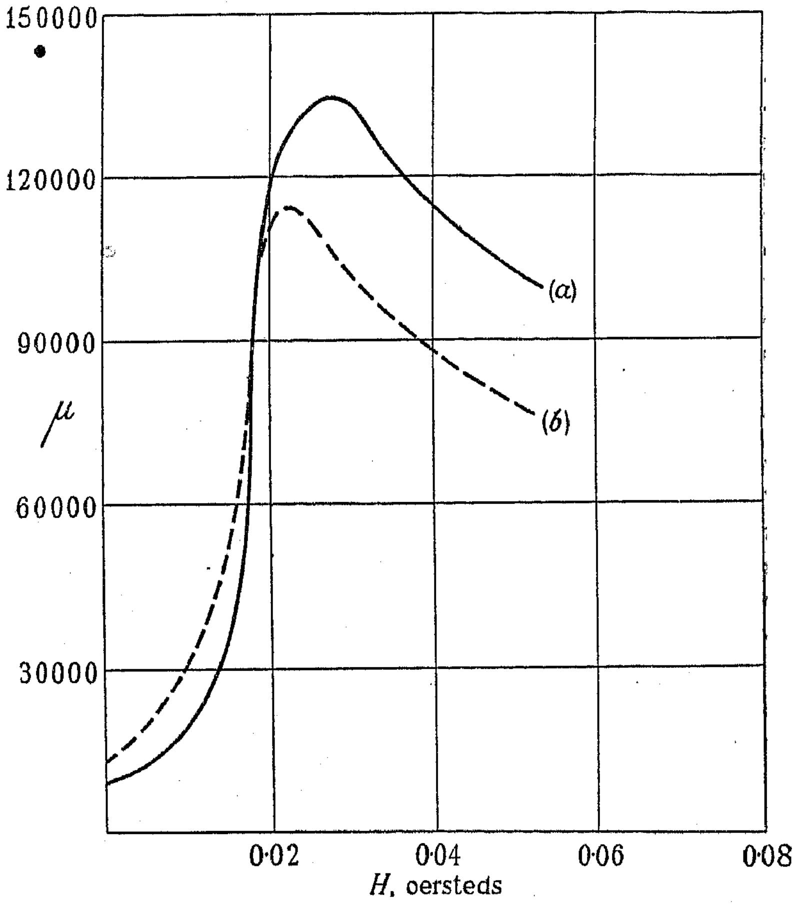


Fig. 2.—Effects of varying heat-treatment in producing (*a*) highest maximum permeability, (*b*) highest initial permeability, in the same sample of mumetal strip.

(i) A temperature sufficient to cause rapid recrystallization of cold worked metal (in practice, 1 150–1 200° C.).

(ii) Rapid attainment of the maximum temperature in order to prohibit, as far as possible, a random grain growth at intermediate temperatures.

(iii) Arrangement of the pieces to be annealed so that all parts cool at as nearly an equal rate as possible. This necessitates packing in a medium with high heat conductivity, and the use of specially-shaped annealing pots so as to allow equal cooling from all surfaces.

The annealing process may be adjusted to some extent to give highest magnetic permeability at different fields (see Fig. 2). This follows if hypothesis (iv) is correct, for with rapid cooling after heat treatment the internal stresses are greater than with a slower rate, and greater magnetostrictive strains may be neutralized thereby.

---

* *Physics*, 1934, vol. 5, p. 169; *Physical Review*, 1934, vol. 45, p. 742.

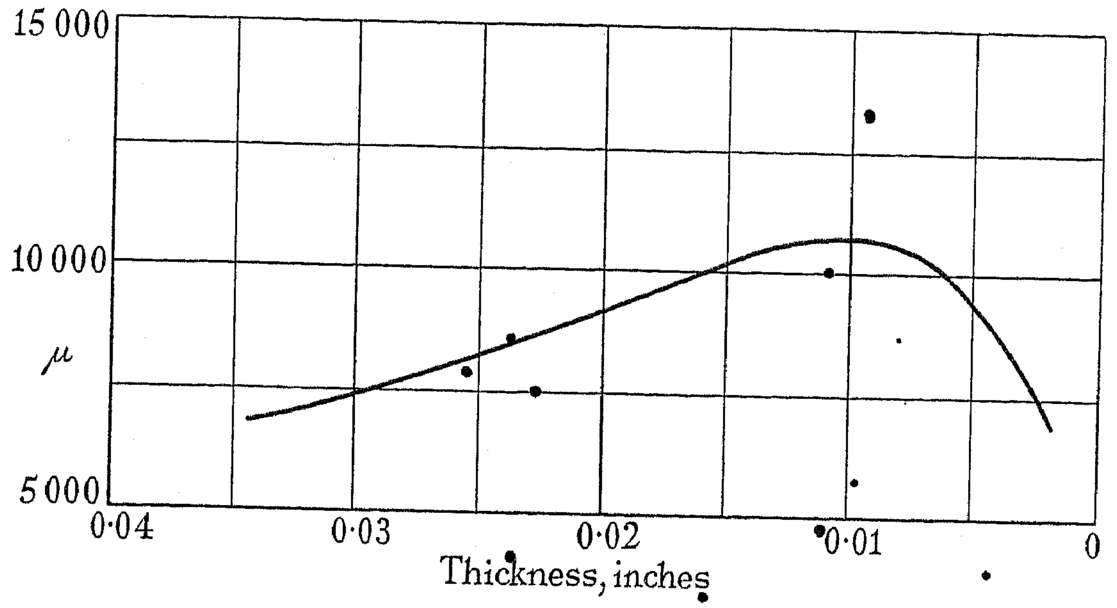


Fig. 3.—Average variation of initial 50-cycle permeability with thickness of strip (commercial samples).

Equilibrium conditions are therefore obtained at higher magnetic fields, where magnetostrictive effects are greater. The best "permeability conditions" are thus obtained at the higher field.

These high-permeability alloys lie very close to the zero-magnetostriction range of composition, and in consequence are strained to a small extent only by magnetization. The compositions are such that furnace cooling or air cooling in boxes give the internal conditions necessary for high permeability. The same object can be achieved by a duplex process, as follows: First, cooling from a high temperature, thus intensifying the conditions of internal strain; second, partially relieving the stresses by subsequently reheating to a lower temperature, namely 600° C.; finally, slow cooling to air temperature, which fixes these conditions. This series of operations is capable of controlling the product more exactly than the direct cooling process, and was evolved at the Bell Telephone Laboratories, where it was found essential for the treatment of permalloy in its early days. Direct cooling is, however, less cumbersome for practical use and gives very reliable results with alloys which have been adapted in their manufacture to that particular method of treatment.

(5) GENERAL CONSIDERATIONS AFFECTING MANUFACTURE

(a) Thickness of Strip

For reasons connected with manufacture which can be understood from the working effects mentioned above, there is, practically, an optimum range of thickness for strip over which high permeabilities are most readily developed. The upper limit is set by the economic difficulty of obtaining a sufficient degree of working in the heavier gauges and also by the less uniform cooling occasioned by greater thickness. On the other hand, the effect of non-orientated surface layers becomes increasingly important as the thickness is decreased, and permeability falls off. In practice the range may be taken to extend from about 0·025 in. to 0·008 in. A typical range of variation is shown in Fig. 3. These remarks apply, of course, to 50-cycle operation; at higher frequencies these effects are offset by the advantage obtained from using thinner strip.

(b) Direction of Magnetization

The method of production of strip by controlled cold-rolling determines the grain orientation, which is such that maximum permeability occurs in the direction of longitudinal extension, i.e. along the strip. It will be evident, therefore, that if the maximum permeability effects are desired, design should be such that the direc-

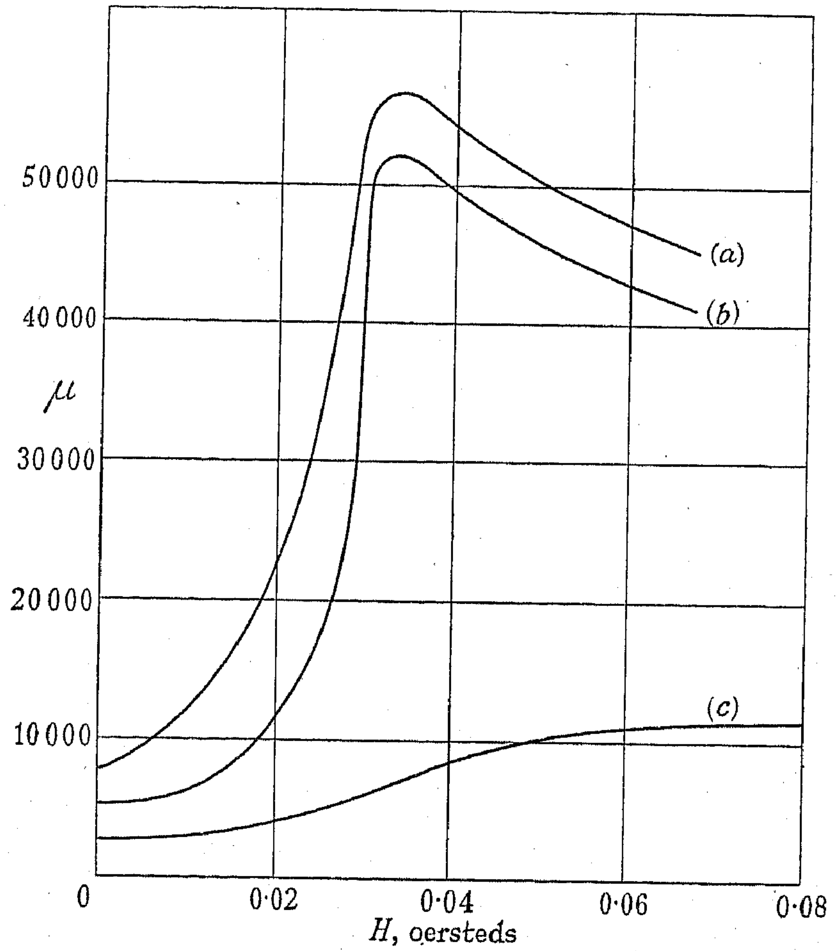


Fig. 4.—Variation of permeability with rolling direction: strip, 0·015 in. thick.

(a) Flux parallel to rolling direction.
(b) Flux at 45° to rolling direction.
(c) Flux at right angles to rolling direction.

tion of flux follows the rolling direction. This condition is realized in spirally-wound cores, but cannot be obtained completely with laminations of the "L," "E," "U," or ring type. For this reason, the effective permeability on a core made up in clock-spring form is higher than on a similar core made up from stampings. The variation of permeability in various directions of strip produced by controlled cold-rolling is shown in Fig. 4, and comparative B/H curves for spiral and strip cores are given in Fig. 5.

(c) Distortion and Strain

The effect of mechanical strain on high-permeability alloys has been sufficiently emphasized. As far as possible all mechanical operations—even finishing, such as filing or polishing—should be completed before the final heat treatment is carried out. When laminations are being stacked, care should be taken that the pressure exerted is no greater than is just necessary to hold the stampings together, and similarly when windings are applied care should be taken to see that they are not put on too tightly.

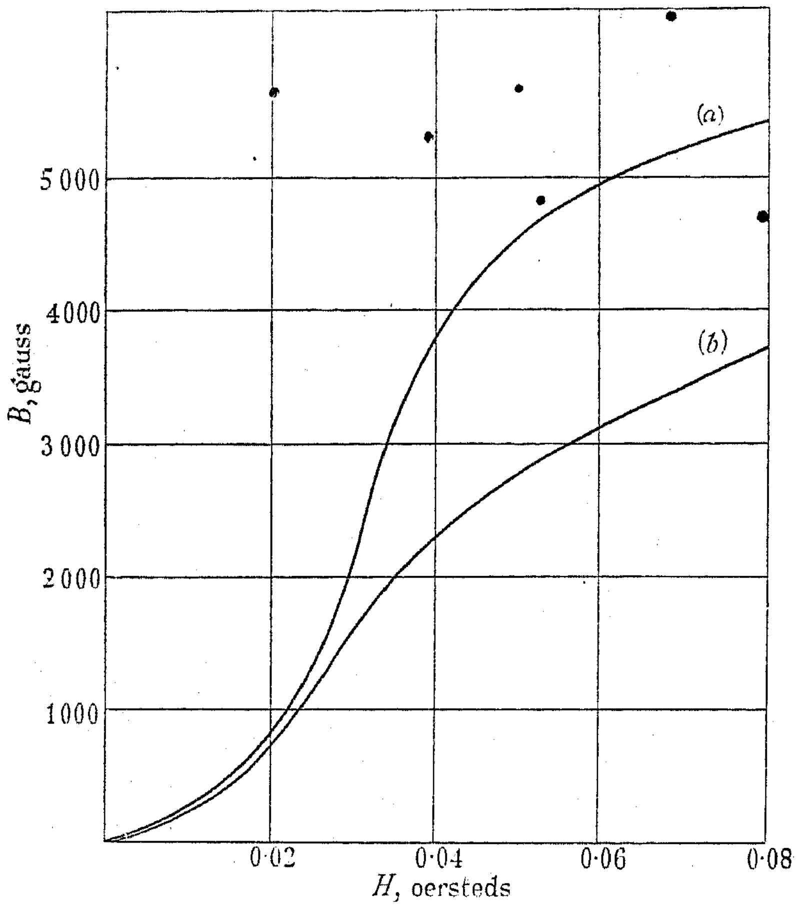


Fig. 5.—B/H curve for mumetal strip, 0·015 in. thick.

(a) Continuous strip-wound spiral core.
(b) Core built up from cut strips.

(d) Effect of Joints

With these high-permeability alloys the effect of butted joints is proportionately much greater than with low-permeability cores. If the joints are carefully machined before assembly the results obtained may approximate to the true permeability values, but with ordinary assemblies the effect is very considerable. When it is desired to take full advantage of the high permeability, continuous strip cores should be employed.

(e) Continuous Strip Cores

Strip cores are not always convenient owing to the impossibility of applying ready-made windings, but one of the reasons for the use of strip cores as against stampings has already been given, namely directionality of magnetization. Also, little scrap is produced in their manufacture, and no stamping charges are incurred, so that the initial cost is lower than that of a built-up core. The internal and external diameter may be adjusted to any size, and the core may be built up in sections to any depth. In order to control heat-treatment strains, such cores cannot be made up tightly, and for most purposes they require "solidifying" with a carefully chosen wax before being wound. For oil-immersed instruments such a solidified core is wrapped and protected by a non-oil soluble material.

If a long axial length is desired, the core is best made up from a number of units of standard length. This is for two reasons: firstly, eddy-current losses are increased by extending the axial length; and secondly, the difficulties of heat treatment are increased and the developed permeability is generally not so high as on narrower cores.

The result of increasing the radial width is that the effective permeability over the whole is reduced owing to the difference in length of the magnetic path on the inside and outside of the core. This effect is much more pronounced in these alloys with a high range of permeability at low inductions than with the less permeable iron alloys.

(f) Insulation

The superficial layer of oxide formed on the surface of the alloys during heat treatment is, if properly controlled, sufficient electrical insulation to render further precautions unnecessary. Very little advantage in reduced losses results from spraying or varnishing.

(g) Absence of Ageing Effects

Although the effect of any mechanical deformation is very damaging, it should be borne in mind that if the material is in the heat-treated condition the diminution in permeability is restricted to the area actually deformed or strained, so that the total effect may not be very noticeable. Vibration or shock which does not result in actual deformation is not damaging. Ageing phenomena are notably absent, as is evidenced by the National Physical Laboratory's reports (1933) on their standard current transformers and also by the constancy of the characteristics of loaded submarine cables which have been in operation for 12 years.

(6) MAGNETIC CHARACTERISTICS

(a) General

It is apparent that the factors affecting the magnetic properties of high-permeability alloys are many and varied, and if all these factors can be brought to an optimum condition simultaneously remarkable results may be obtained. In such circumstances a permeability of 600 000 has been recorded,* but commercial production demands some tolerance in all directions and such figures cannot be obtained in practice. It is possible, however, to give definite minimum curves which are progressively improved with wider knowledge of the materials. When utilizing the curves given below one should remember that individual samples will not have properties corresponding in detail with all the curves. The figures given, having been taken from average results, form a working basis for calculation.

---

* R. M. Bozorth: *Physical Review*, 1934, vol. 46, p. 232.

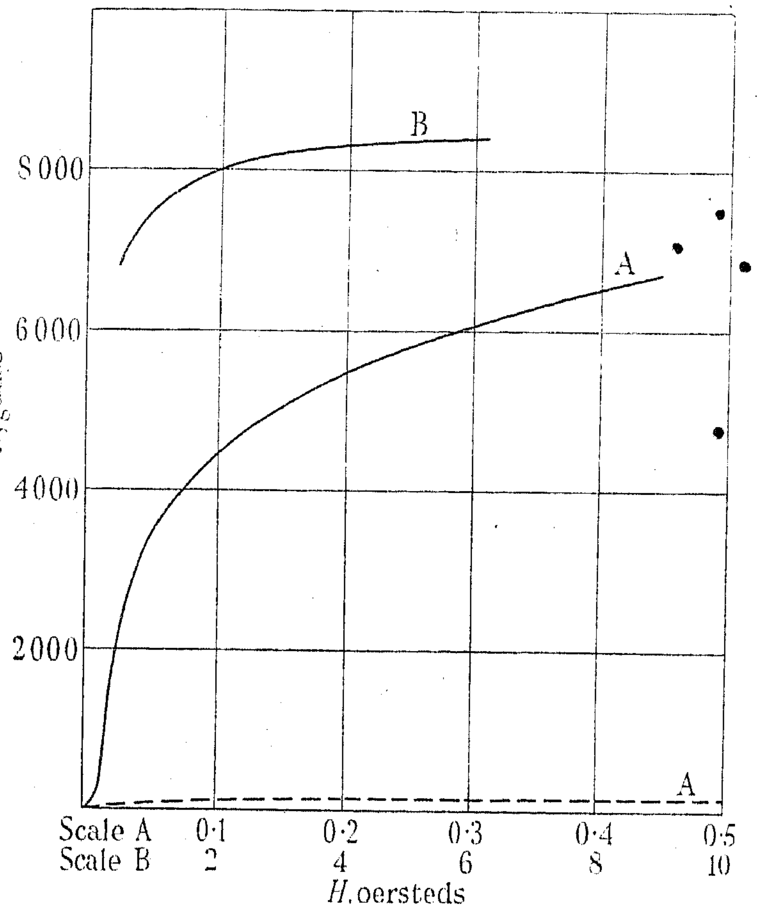


Fig. 6.—D.C. magnetization curves.

Broken-line curve indicates d.c. magnetization of nickel-iron alloy before annealing.

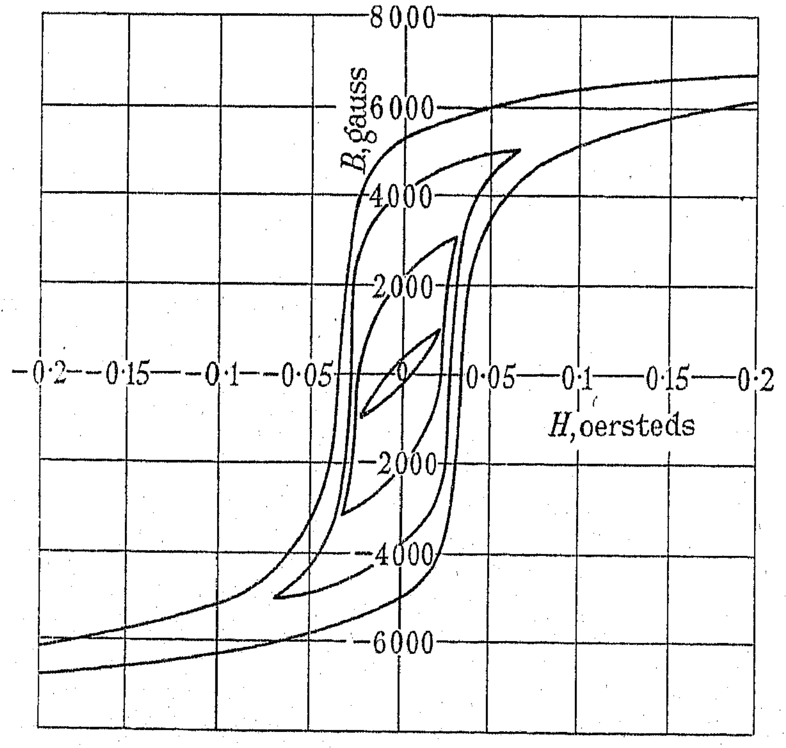


Fig. 7.—Hysteresis loops for mumetal.

(b) Normal Induction Curve

The saturation induction of the high-permeability nickel-iron alloys is in the region of 10 000 gauss, i.e. less than half the saturation induction of pure iron. The "knee" of the curve occurs generally at 6 000–7 000 gauss (see Figs. 6 and 7). The remarkably low coercivity (about 0·03 oersted for $B_{max.} = 8\ 000$) is characteristic. The remanence is about 80 per cent of $B_{max.}$ The permeability is greatest in the region about 0·03 oersted, but in those cases where exceptionally high permeability is developed this occurs at lower fields—down to 0·015 oersted. The initial permeability is not, of course, measurable, and the figures given for this are obtained from measurements made with a field of 0·001 oersted. On commercial samples μ_0 may be as high as 30 000 and $\mu_{max.}$ 130 000.

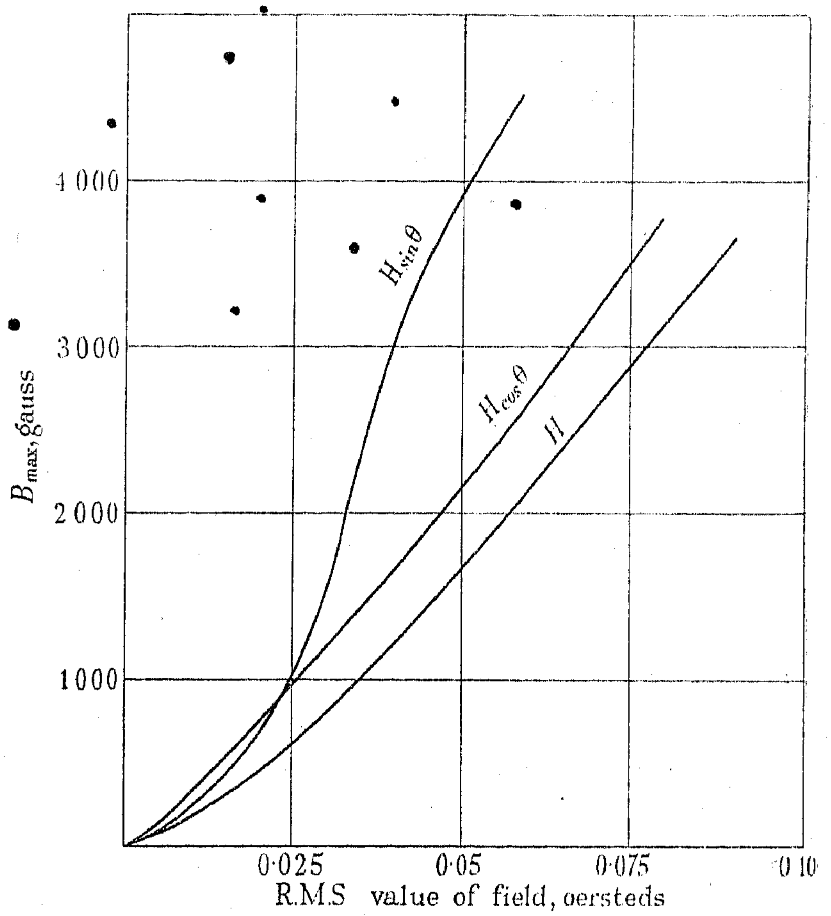


Fig. 8.—A.C. magnetization curves for mumetal strip, 0·015 in. thick.

(c) Losses

The foregoing figures relate to d.c. magnetization. From a.c. measurements (see Fig. 8) a figure for permeability may be derived but this is of little use, and the relative magnitudes of $B_{max.}$ and $H_{max.}$ with the corresponding watt-loss (P) figures are of more value. It is evident from Fig. 7 that the hysteresis losses are very small, and the variation with flux density is given in Fig. 9. The resistivity of the commercial high-permeability alloys is between 45 and 55 microhms per cm cube, and the total losses with 50-cycle magnetization are about one-quarter those of ordinary silicon iron. The total watt losses for 0·015-in. strip—a standard thickness—are given in Fig. 10. It will be seen that $P \propto B^2$ almost exactly, and this relationship holds approximately for thicknesses between 0·004 in. and 0·030 in. Also, $P \propto d^2$ (d being the thickness of the strip) over the range 0·020 in. to 0·008 in., but as the thickness decreases this relation does not remain exactly true, the variation being nearer $d^{1\cdot7}$. For 0·015-in. strip at 50 cycles per sec., $P = 2\cdot7 \times 10^{-9}B^2$.

The curves were obtained from spirally-wound cores with the turns insulated only by the superficial coat of oxide developed during heat treatment.

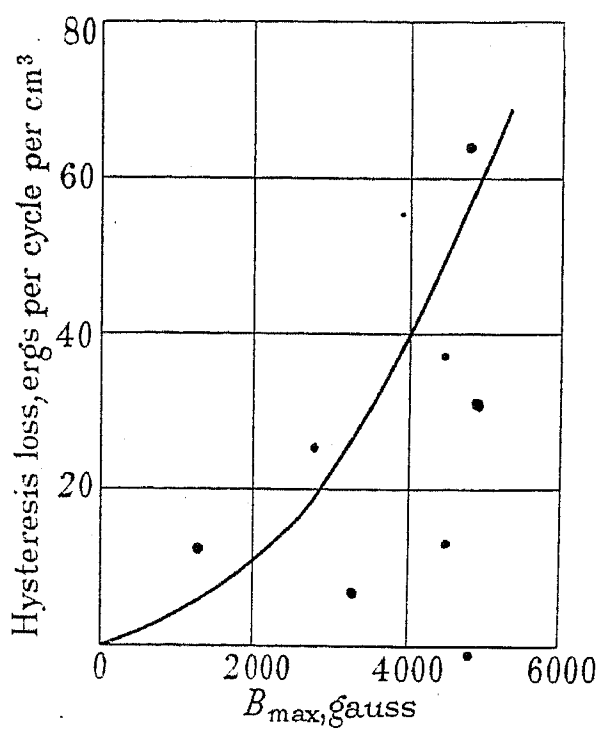


Fig. 9.—Variation of hysteresis loss with flux density.

(d) Characteristics at High Frequencies

The effective magnetization of these alloys diminishes rapidly with increasing frequency, and the watt loss increases proportionately. As one would expect, there is a marked skin magnetization effect, so that thin strips are much more effective under these conditions, the losses being reduced also at the same time by diminished thickness. The relation $P \propto B^2$ is correct, to a first approximation, for frequencies up to 5 000 cycles per sec. The increase of watt loss with frequency, however, for any given thickness of strip, varies as $f^{1\cdot8}$. The losses at 5 000 cycles for two different thicknesses are given in Fig. 11. For 0·004-in. strip at 5 000 cycles, $P = 8 \times 10^{-6}B^2$. Figs. 12 and 13 show the variation of flux density with total field at two different frequencies.

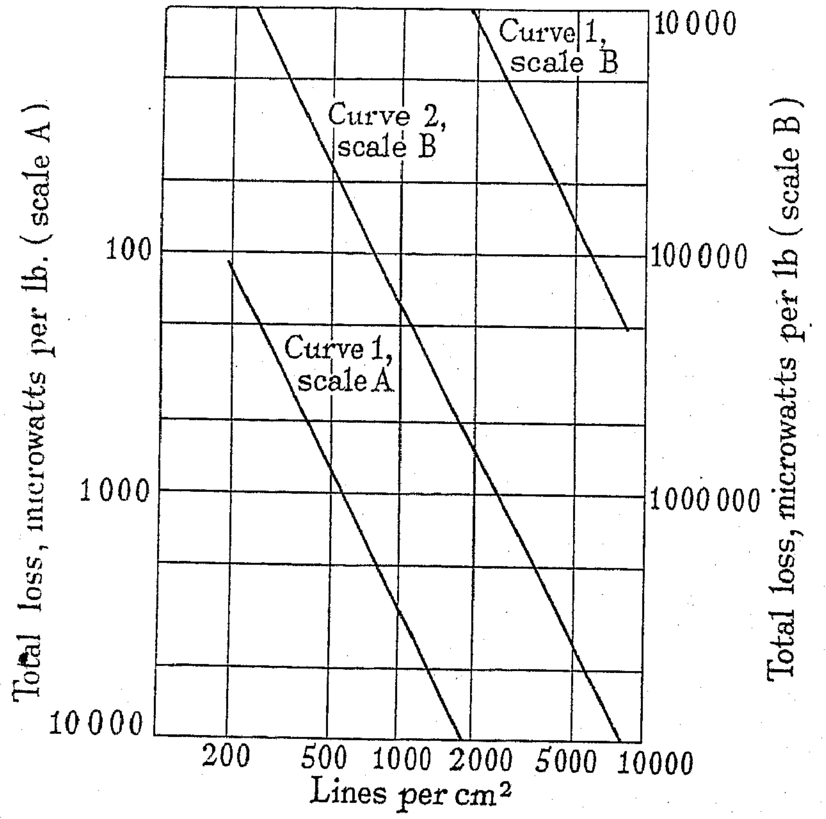


Fig. 10.—Total watt loss for 0·015-in. mumetal strip.
Curve 1. Results obtained at 50 cycles per sec.
Curve 2. Results obtained at 600 cycles per sec.

(e) Incremental Permeability

As these alloys are saturated by the application of quite small magnetizing forces, it is to be anticipated that polarizing fields will seriously affect the effective permeability under a.c. conditions. The rapid decrease in this incremental permeability is illustrated in Fig. 14. It will be seen that with initial a.c. fields a d.c. polarizing field of 0·5 oersted is sufficient to reduce the permeability to 2 000, although at higher frequencies the effect is not so marked.

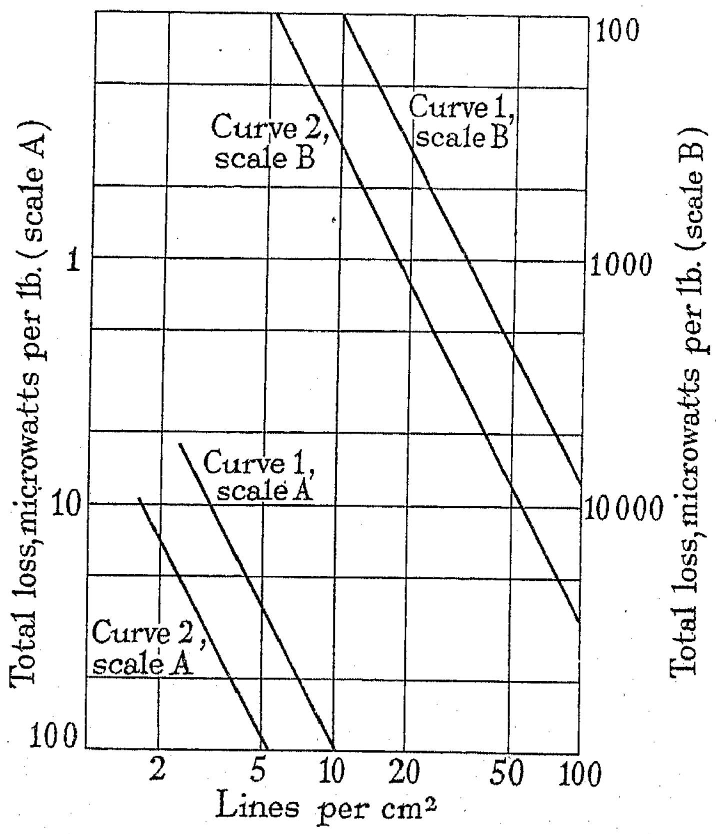


Fig. 11.—Total watt losses at 5 000 cycles per sec. for two different thicknesses of mumetal strip.
Curve 1. 0·004 in. thick.
Curve 2. 0·008 in. thick.

(7) TESTING METHODS

Magnetic testing and control of high-permeability alloys demands more exact conditions than are required for the less permeable materials employed for similar purposes. The following notes on the methods employed in the control of mumetal may therefore be of interest.

(a) D.C. Tests

In order to determine experimentally d.c. permeability and B/H curves, use is made of the well-known ballistic-galvanometer method. The standard consists of a long tube with primary and secondary of known turns and dimensions, of which the mutual inductance can be estimated and measured with accuracy. The galvanometer is of the reflecting type, and by means of the

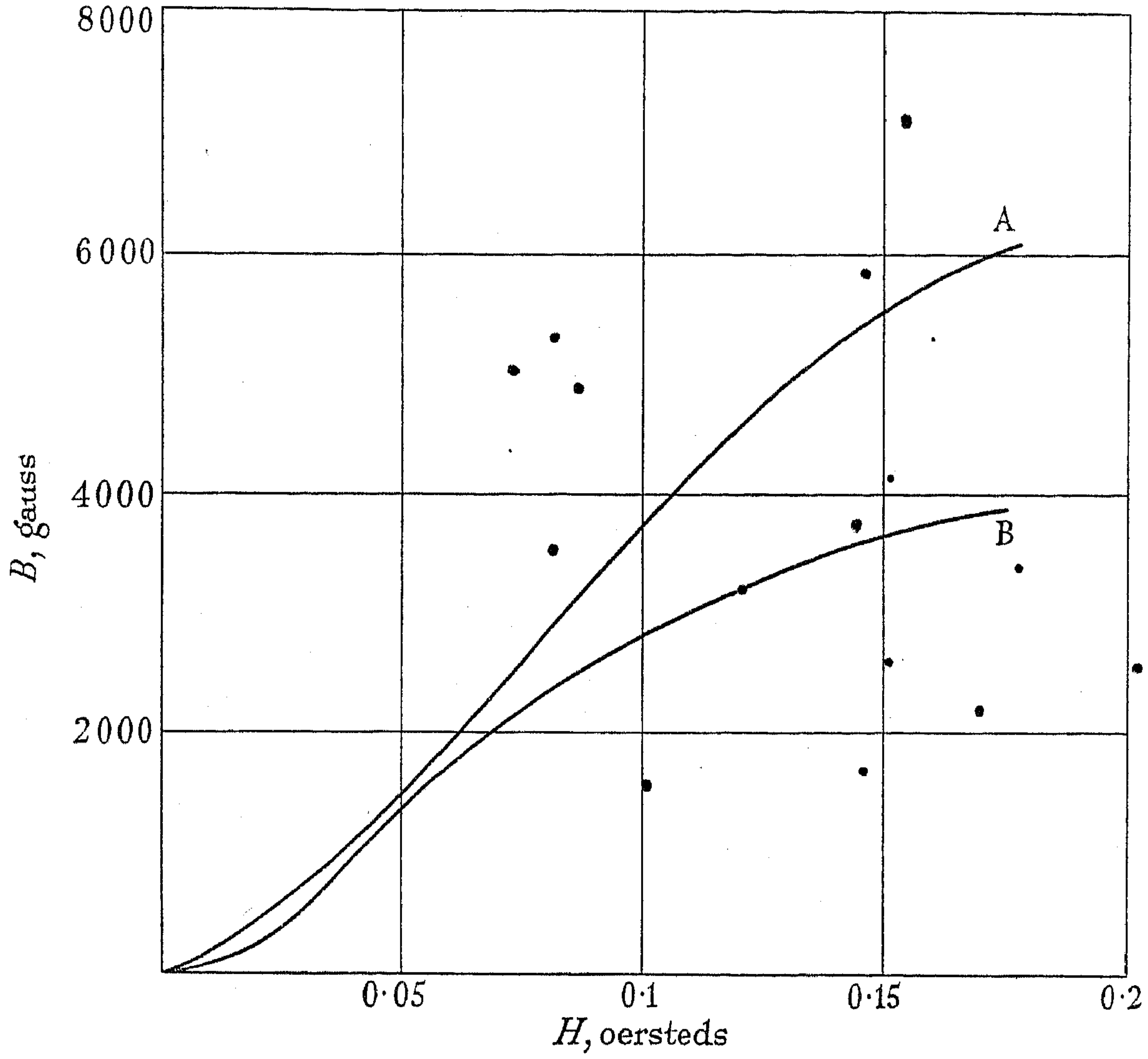


Fig. 12.—Variation of flux density with total field (r.m.s.), at 50 cycles per sec., for two different thicknesses of mumetal strip.

Curve A. 0·015 in. thick.
Curve B. 0·005 in. thick.

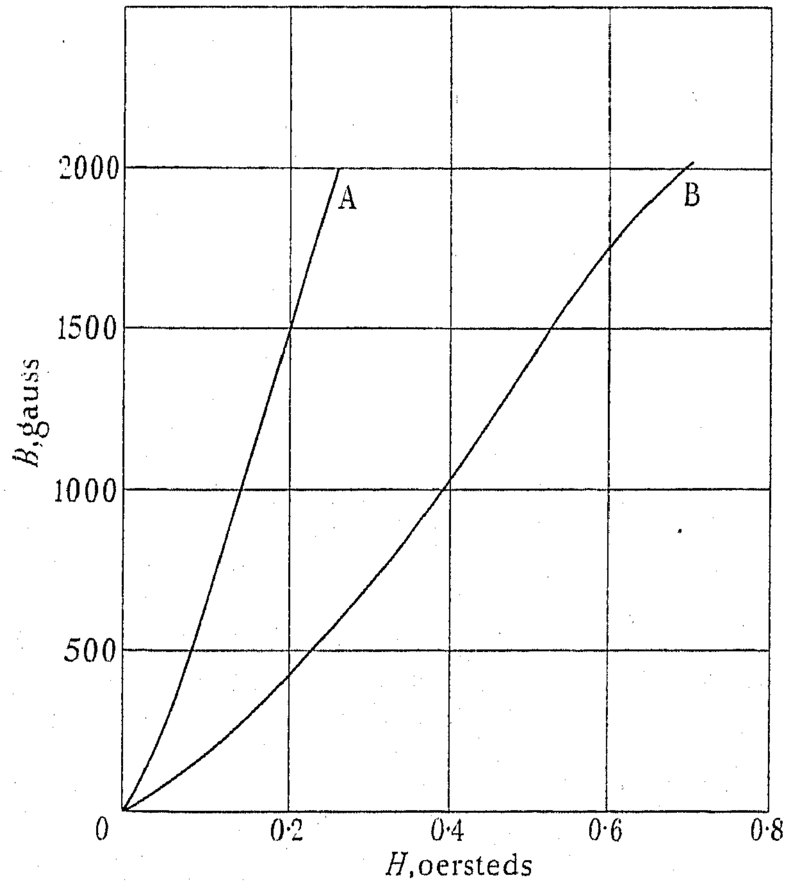


Fig. 13.—Variation of flux density with total field (r.m.s.), at 2 500 cycles per sec., for two different thicknesses of mumetal strip.

Curve A. 0·005 in. thick.
Curve B. 0·015 in. thick.

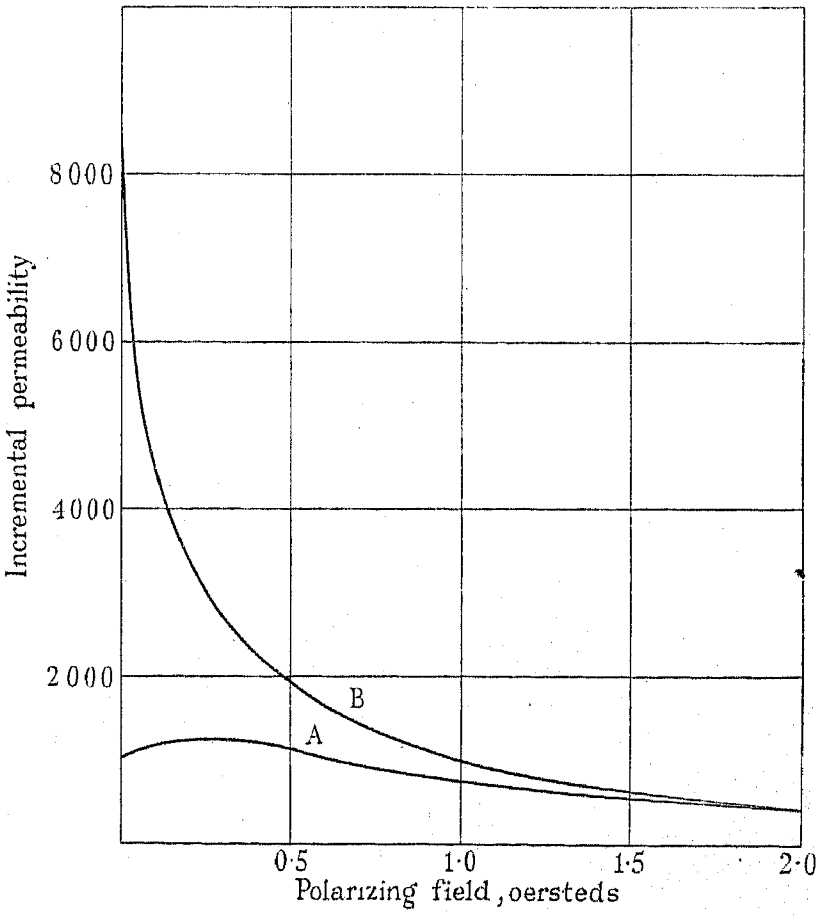


Fig. 14.—Incremental-permeability curves for 0·015-in. mumetal sheet.

Curve A. Alternating-current field 0·005 oersted, 1 000 cycles per sec.
Curve B. Alternating-current field 0·005 oersted, 50 cycles per sec.

standard can easily be calibrated immediately prior to a test.

The magnetic sample is uniformly wound with the requisite primary and secondary turns, and is normally demagnetized before test by passing 50-cycle alternating current through the primary and slowly reducing the current to zero.

(b) Magnetic Shields

The same galvanometer is also employed to obtain information on the screening properties of nickel-iron-alloy magnetic shields. Direct current is passed through a short solenoid whose iron core has an appreciable stray magnetic field, and arrangements are made for easily reversing this direct current. A suitable search coil is placed within the stray field, and galvanometer deflections are observed for reversals of this field, (i) with the search coil enclosed within the magnetic screen, and (ii) with the magnetic screen removed. The search-coil pick-up is considerably reduced by the screen, and the resulting ratio is used as a control on the annealing of the screening material.

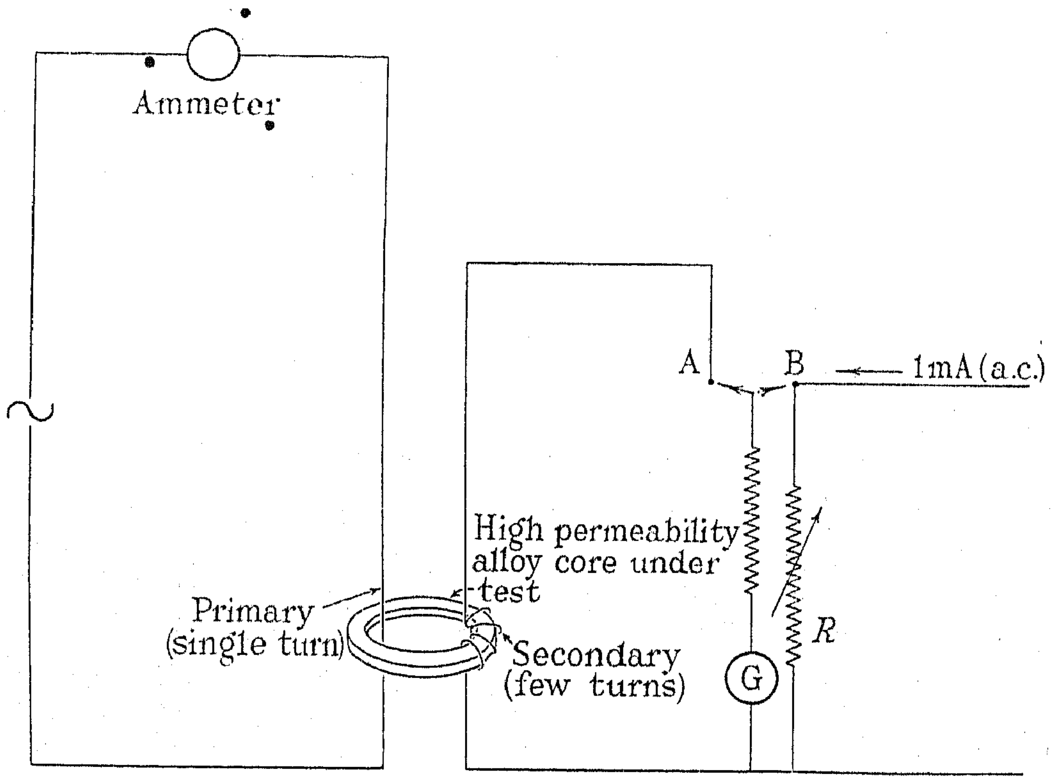


Fig. 15.—Factory method for obtaining *B*/*H* curves of high-permeability alloys at 50 cycles per sec.

(c) A.C. Tests

Since the bulk of the high-permeability alloys are employed under alternating-current conditions, information on inductance, effective resistance, *B*/*H* characteristics, and watt loss, is essential. Many forms of a.c. bridge are suitable for this purpose, but the most flexible is the well-known Heaviside inductance bridge. This permits the measurement of all the above properties over the working range of currents and frequencies, and gives results of good accuracy.

(d) Loaded Submarine-Cable Testing

In the manufacture of loaded submarine cables it is desirable to measure the inductance per unit length of loaded conductor during annealing and prior to the gutta-percha covering operation. This measurement not only controls the annealing but also gives an indication of the final performance of the cable.

The loaded conductor, after passing through the tubular furnace, is arranged to pass over electric contacts permitting a 10-ft. length of conductor to be tested at any instant. This length of conductor constitutes the fourth arm of a simple bridge whose constants are chosen so that the out-of-balance current is proportional to the conductor inductance. This out-of-balance current is measured on a Sumpner a.c. galvanometer, the deflection of which gives a direct indication of the effective permeability of the loading material.

(e) Spiral Cores and Rings for Current Transformers

The final performance of current transformers depends essentially upon the magnetic properties of the alloy used, and it is customary to test each core after annealing. Experience has shown that if the alternating-current *B*/*H* curve is within specification the losses invariably follow suit, and on this assumption is based the following simple factory test, the circuit connections for which are shown in Fig. 15.

The primary winding is a single turn carrying a measured current giving a known value of magnetizing force on the core under test. The secondary winding consists of a few turns only, and by the aid of a vibration galvanometer in series with a high resistance a deflection is obtained proportional (very nearly) to the open-circuit secondary voltage. A fixed alternating current of 1 milliampere passes through the variable resistance R, so that, by switching from point A to point B and adjusting R, equal deflections may be obtained. Within certain limits the a.c. flux density is directly proportional to this (secondary) voltage. As a result, rapid determination of the alternating-current *B*/*H* curves is possible.

In the actual equipment the core is passed over a fibre tube on the end of which is a plug-and-socket device enabling the equivalent primary and secondary windings to be applied with the single operation of inserting a multi-point plug.

(8) INDUSTRIAL APPLICATIONS

(a) Cable Loading

It has been stated that the necessity for loading submarine telegraph cables was the prime reason for the development of mumetal. As signalling conductors are made longer, the increased capacitance causes attenuation and practical obliteration of the signal definition, so that the possible speed of working is much reduced. By increasing the self-inductance of the cable—while taking good care of the additional electrical losses consequent upon it—this effect may be nullified. This is effected by loading with high-permeability alloys. Owing to the small amplitude of the current in the distant parts of such conductors, a high permeability in " initial " fields is essential if any considerable increase in inductance is to be achieved without an excessively heavy loading which would bring the cost of the cable to a figure greater than that of an equally effective unloaded conductor. Low hysteresis losses are also desirable, as the effective resistance may be largely increased. For this purpose the alloy is drawn to fine wire 0·006 in. to 0·008 in. diameter, or rolled to narrow tape of about the same thickness. Owing to the stresses involved when spiralling this on to the copper, it is necessary to anneal subsequent to this process, and this is done by drawing the loaded conductor through a tube furnace. Coil annealing presents difficulties owing to the rate of cooling. The method employed also lends itself to continuous control, and the inductance of the cable is read continuously during passage through the furnace by the arrangement already mentioned.

Loaded telegraph cables already laid have 5–10 times the message capacity of similar unloaded cables.*

(b) Instrument-Transformer Cores

The advantages which may be obtained from the use of high-permeability alloys as the core of instrument transformers are well appreciated by designers, and this application has been adequately dealt with in the *Journal* and elsewhere during the last few years.† The single-turn or straight-through primary can be more generally employed than with the old " irons." The permeability of the new alloys being much higher and the losses lower than those of silicon iron, the phase-angle and ratio errors can be much reduced, and the weight of material necessary for the improved results is much less. In fact, before the use of high-permeability cores became commonplace and when silicon iron was accepted as a standard, the errors were lower than the limit of accurate determination by existing apparatus, and current transformers were approved with " zero " errors. High-permeability cores have now made these small errors measurable.

(c) Transformers and Chokes for Radio Apparatus

The current dealt with in this type of apparatus is generally of very small magnitude, and the use of a core material with high magnetic permeability in small fields offers great advantages when high inductance is desirable; the intervalve transformer necessary for low-frequency amplification is a case in point. Inductances much higher than those obtainable with silicon iron are possible with very small cores, and an amplification characteristic may be obtained about constant from 50 to 20 000 cycles. But precautions are necessary: the instrument must be so employed that there is no strong polarizing current flowing through the windings, for under such conditions the incremental permeability may be lower than that of silicon iron, and the inductance falls off.

As an example, with twelve stampings of $1\frac{1}{2}$ in. × 1 in. overall dimensions, weighing 0·04 lb., an inductance of 80–100 henrys may be obtained, so that there is a large saving in weight and in winding costs at the same time.

A cognate application occurs in the design of low-frequency chokes, where high inductance is of first importance. In such applications absence of transformer noise is important, and the high-permeability alloys with their virtual absence of magnetostrictive effects are much freer from vibration than silicon iron.

(d) Magnetic Screening

Advantage is taken of the magnetic softness of these alloys for shielding from magnetic interference, or from the polarizing magnetization of the earth's field.* This is particularly important in radio receiving sets, where compactness is desirable and interference may be of magnitudes comparable with the energy usefully employed. The close proximity of the various parts, even with the most careful design, results in the field around one component inductively affecting nearby apparatus so that background noises are experienced in reception. High-permeability boxes properly designed for shielding give a reduction in field strength, as measured by the method described, of 1 000 : 1, and a noise reduction of 40 to 50 decibels may be obtained. The box must of course be magnetically intact, preferably stamped in one piece, with a well-fitting overlapped lid, or, if stamping is not applicable to the design, welded on all joints and with any necessary holes as small and few as possible. The best results are obtained with a multiple-layer design, but this is necessarily more expensive than the simple sheet box, which is quite effective for most purposes. With equal thickness the screening effect is 10–20 times that of ordinary iron.

The benefit of shielding is also appreciated by makers of cathode-ray oscillograph tubes. Deflection of the electron stream by outside interference is prevented by a sleeve of mumetal over the neck of the tube, the sleeve being extended by a funnel-shaped end when a greater degree of protection is desired.

Protection of high-sensitivity galvanometers is accomplished more effectively and economically now that high-permeability alloys are available.†

---

* See O. E. Buckley: *Transactions of the American I.E.E.*, 1925, vol. 44, p. 821.

† R. S. J. Spilsbury and A. H. M. Arnold: *Journal I.E.E.*, 1930, vol. 68, p. 889; A. H. M. Arnold: *Journal of Scientific Instruments*, 1931, vol. 8, p. 154; C. V. Drysdale: *Journal I.E.E.*, 1931, vol. 69, p. 170; A. H. M. Arnold: *ibid.*, 1931, vol. 69, p. 156.

* See A. V. Hill: *Journal of Scientific Instruments*, 1926, vol. 3, p. 335; and T. E. Sterne: *Review of Scientific Instruments*, 1935, vol. 6, p. 324.

† See C. V. Drysdale: *Journal I.E.E.*, 1933, vol. 72, p. 365.

(e) Magnetic Relays

The rapid growth of flux with increasing magnetizing force, combined with low coercivity and low hysteresis loss, make these alloys particularly suitable for the cores of magnetic relays in which sensitivity is a first consideration. Advantage can only be taken of the increase in power when core and armature are set very closely together, owing to the effect of the air-gap. As saturation occurs at 10 000 lines per cm^2, more powerful relays may be made with other core irons, but a limit is set to the sensitivity obtainable in these instruments by the coercivity of the core. The low value of this characteristic together with the easy magnetization of the alloys under consideration assure a rapid response to magnetic impulses, and, for this reason, the alloys are utilized in the construction of telegraphic printers and automatic telephone relays. These show a marked improvement in response when results are compared with those obtained on soft-iron cores.*

The following figures obtained from a polarized relay operating railway signals—a case where minimum time-lag and certain action are of the utmost importance—demonstrate this point.

(i) Normal type of relay, with iron core: minimum pick-up current, 59 milliamps.; maximum release current, 42 milliamps.

(ii) Same type of relay, with mumetal core: minimum pick-up current, 41 milliamps.; maximum release current, 36 milliamps.; the on/off current ratio is increased by nearly 20 per cent.

It is important to note that in this and many similar applications the alloys are called upon to withstand atmospheric conditions, and the high resistance to oxidation which is characteristic of high nickel alloys is of particular value.

(f) Armatures for Moving-Iron Instruments

Ease of magnetization, and rapid loss of magnetism after the m.m.f. has been removed, are of importance in the moving irons for measuring instruments. By the use of these alloys such meters may be made with an accuracy comparable with that of the moving-coil type, a much wider scale than heretofore being made possible.* The very small hysteresis losses make the instruments adaptable to both a.c. and d.c. circuits.

(g) General

These alloys are finding wider applications as their valuable properties, and also their weaknesses, become increasingly appreciated. The prime cost occasioned by the manufacturing and control operations appears high, however, when compared with those of older-established magnetic materials, and militates against the use of the new alloys in directions where in fact manufacturing costs might be reduced by their application.

The author wishes to thank members of the metallurgical staff of the Telegraph Construction and Maintenance Co., Ltd., for assistance in the preparation of this paper. Valuable data and suggestions have also been received from Mr. F. E. J. Ockenden and Mr. J. G. Wellings, to whom the existence of this paper is originally due.

DISCUSSION BEFORE THE METER AND INSTRUMENT SECTION, 8TH JANUARY, 1937

Mr. J. G. Wellings: The development on a commercial basis of mumetal and other similar materials has been responsible for very great advances in the design of current transformers and is a striking illustration of the valuable services which the metallurgist can render to the electrical engineer.

It should be realized that, roughly speaking, the permeability of mumetal over the range of flux densities usually employed in current-transformer design is about 10 times that of silicon steel; and although, strangely enough, the price of mumetal is also about 10 times that of stalloy, there is undoubtedly justification in a very large number of cases for the use of the more expensive material.

While the comparatively low saturation flux density of mumetal imposes no serious handicap on instrument current-transformer design, I should like to ask the author the reason of the low saturation density and also whether there is any possibility in the future of the value being raised. In current-transformer design the low saturation density is a slight advantage in one respect since it reduces the open-circuit voltage, although the peak value may still be dangerously high.

A serious limitation which existed when mumetal and other similar materials were first introduced was instability due to shock and over-magnetization. This, however, has now been overcome, and mumetal may be regarded as reasonably stable, provided no sharp bending or punching operation is carried out after the annealing process.

I should like to endorse the author's remarks regarding the higher permeability obtained on ring cores of rolled strip as compared with annular punchings. It might at first be thought that the superimposition of a circular flux upon a spiral magnetic path must involve an air-gap effect. Experience and tests, however, show that this is not detrimental and probably the explanation is that the area of the effective gap is equal to the superficial area of the whole length of strip of which the core is composed. The flux density in the effective gap is therefore low, and what little adverse effect is produced thereby is more than counterbalanced by the advantage obtained with the increased permeability due to the flux always lying in the direction of the grain of the material. In an annular punching over half the circumference the flux is necessarily traversing the material across the grain.

I should like to refer to what may be termed the high "differential permeability" of mumetal. This is quite different from what the author terms the "incremental permeability." By differential permeability is meant the rate of increase of flux density with magnetizing force, which, between certain limits of flux density (usually 10 to 20 kilolines per sq. in.), is much greater than the permeability at lower densities. This is shown in Fig. A.

---

* See A. E. TATTERSALL: *Journal of Scientific Instruments*, 1935, vol.12, p. 341.

* See A. V. HILL: *Journal of Scientific Instruments*, 1926, vol. 3, p. 335.

Means by which advantage may be taken of this feature are described in British Patent Specification No. 286431, and a simple bar-primary current transformer adapted to this purpose is shown in Fig. B. The main core carrying the secondary winding is divided into half-sections which are magnetized in opposite directions by a "figure eight" winding energized from a separate core. The flux due to such auxiliary magnetization can produce no e.m.f. in the secondary winding on account of the equal and opposite effects of each half of the section of the core. By design the auxiliary winding is arranged to magnetize the half-sections of the core to a flux density represented by the point X in Fig. A, which corresponds to approximately the mid-point of the optimum range of differential permeability. The flux density due to the secondary voltage therefore adds to or subtracts from this degree of auxiliary magnetization X, for example, by an amount represented by XP or XQ. The magnetization required for the flux density X to P is obviously much less than that required for the same value if starting from the zero point of the curve instead of the point X. In practice, for a given size of core, this permits of the magnetizing current being reduced to about one-third of what would otherwise be required, and the errors are therefore proportionately reduced. Conversely, for a given accuracy, the size of core can be reduced; this is a great advantage, for example in the design of low-ratio high-accuracy transformers mounted in high-voltage bushings. Other means whereby the accuracy may be still further improved by other types of compensating windings, or alternatively the size of core may be reduced for a given accuracy, are described in a paper* on "Instrument Transformers," which was read before this Section in January, 1930.

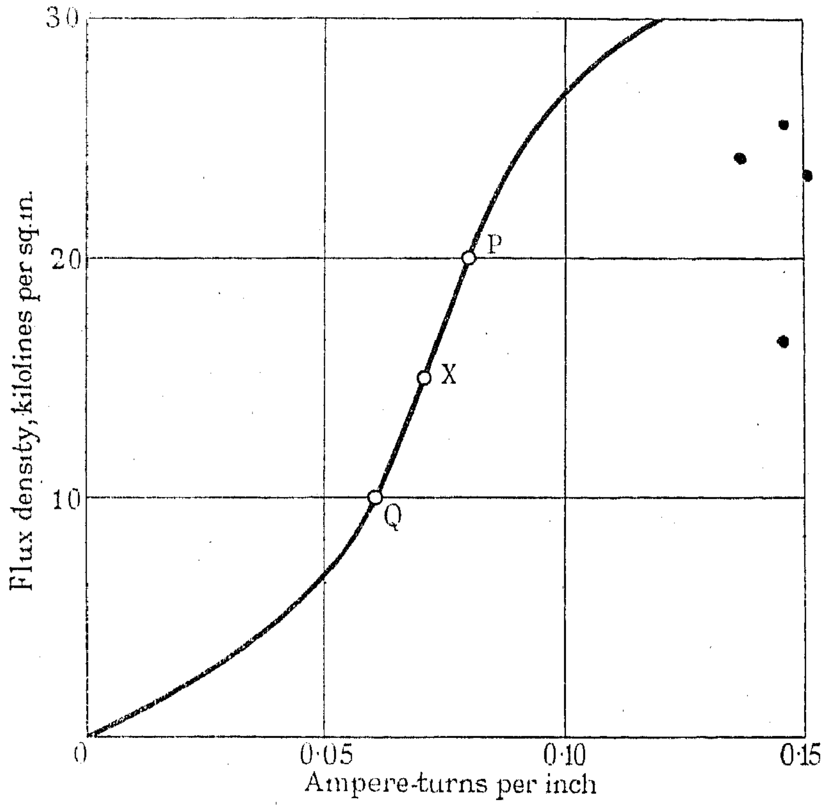


Fig. A.—Differential permeability of mumetal.

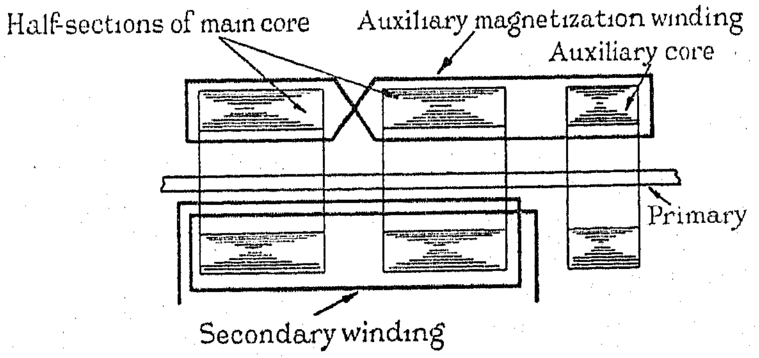


Fig. B

Mr. C. E. Webb: Of the theories mentioned as having been put forward to account for the development of high permeability in nickel-iron alloys, (i) and (iii) have never received any direct confirmation, while with regard to (iii) Jette and Foote† have within the last year conducted an X-ray examination of iron-nickel alloys directly aimed at the detection of a super-lattice but have failed to find any trace of one. The influence of impurities, involved in theory (ii), is undoubtedly important, but, as Yensen has shown in his fundamental researches on iron and iron-silicon alloys, is very complicated. Recent evidence strongly supports the view that the decisive factor in the production of the exceptionally high permeabilities of permalloy and mumetal is that stated in theory (iv), namely the possibility of minimizing internal strain, which results from the small magnetostrictive stresses in these alloys. Thus Von Auwers and Neumann,‡ in their systematic investigation of the iron-nickel-copper alloys, found a range of composition, which was little affected by heat treatment, for which the initial permeability was high, and a closely related range of composition for which the magnetostriction was zero. The largely increased permeability obtained in certain iron-nickel alloys by cooling in a magnetic field, to which the author refers, also appears to be explicable only by the relief of magnetostrictive stresses by plastic flow at high temperatures. Even for this theory, however, the evidence is not entirely consistent, as it has been pointed out that the effect of cooling in a magnetic field ought, according to the theory, to be present at the iron end as well as the nickel end of the series, whereas it is almost completely absent. Any experience which the author may have had in this connection would be of interest.

The author mentioned verbally the alloy "1040," developed in Germany, for which an initial permeability of the order of 40 000 has been claimed. Has he had experience of the properties of this type of alloy? Are the properties claimed obtainable commercially?

I am glad to see that the author emphasizes the importance of avoiding stresses in the material due to windings, and also of expressing the a.c. permeability in terms of the maximum values of B and H. I am surprised that Fig. 14, curve A, shows an increase of incremental permeability as the polarizing field-strength is increased, as I have always found—chiefly at lower frequencies—that the curve falls continuously. Has the author any theory to account for the increase in this case? The striking figures given on page 657 for the weight and inductance of a choke with a core of nickel-iron stampings would be even more impressive if comparable figures for silicon-iron were provided.

---

* J. G. Wellings and C. G. Mayo: *Journal I.E.E.*, 1930, vol. 68, p. 704.

† *Metals Technology*, 1936, vol. 3, No. 1.

‡ *Wissenschaftliche Veröffentlichungen aus den Siemens-Werken*, 1935, vol. 14, p. 93.

Mr. J. H. Buchanan: Strip-wound cores give very much better results than built-up cores, whether built of straight strips or of die punchings, and the fundamental reasons for this are not made quite clear in the paper. The direction of the grain and the introduction of joint reluctance are fairly obvious causes of a poorer result in the case of a built-up core, but there is another very important cause. It is usually necessary to clamp a built-up core by applying pressure to the laminations, and the resultant mechanical stress has a detrimental effect on the characteristics of the mumetal. In the case of a.c. magnetization the clamping also causes increased eddy-current losses, which result in a further apparent deterioration of magnetic characteristics and necessitate the provision of effective insulation on the laminations. It is difficult to obtain a varnish which is sufficiently thin and even to give the required insulation without adding perceptible reluctance at the joints, and I agree with the author that a good oxide film is the best form of insulation to use. It is important to remember that, owing to the relatively low reluctance of mumetal, an additional reluctance at the joints, which would be unnoticed in a silicon-steel core, may be very noticeable in a mumetal core.

The various applications of mumetal require such distinct types of characteristics that a more sharply-defined grading of the material for different purposes should be considered. Even for current transformers it would be an advantage to have two different types of characteristic. In the revised British Standard Specification for instrument transformers (B.S.S. No. 81—1936) certain new classes of accuracy are introduced, in which the variation of error over a range of current is specified. When mumetal is employed for such a purpose the variation of permeability over a range of flux densities is therefore important. It is possible in such a case for the variation to be actually increased if the peak permeability is unduly high, and therefore for such a purpose it would be preferable to have a permeability curve showing high initial permeability and only a moderate peak. On the other hand if, as is sometimes done, a mumetal core is used in a current transformer with the object of working a sensitive relay with a very small operating current, then a high permeability peak is desirable.

In Fig. 4 there are three curves, (*a*), (*b*), and (*c*), showing respectively the permeability in the direction of rolling, at 45°, and at right angles, to this direction. Are these curves relatively of the correct height? If so, it would appear that there is very little reduction in the maximum permeability up to an angle of 45° to the direction of rolling, but at right angles there is a very big drop. One important point on which this has a bearing is that laminations are sometimes stamped out in the form of an "L," and, if a lamination is stamped with one side of the "L" in the direction of rolling and the other at right angles, one should get about the mean of curves (*a*) and (*c*). On the assumption that the curves in Fig. 4 are correctly related, it would appear to be very advantageous to punch such a lamination with the side of the "L" at an angle of 45° to the direction of rolling.

Mr. Wellings stated that the stability of the characteristics of mumetal is now as good as that of silicon steel. In actual fact it has been shown that the stability of mumetal is very much better than that of silicon steel.

Dr. E. Hughes: I wish to express my disagreement with the use of the r.m.s. value of the field strength in Fig. 8. This is wrong in principle, because with silicon steels it has been repeatedly shown that the flux density is a maximum when the magnetizing force is a maximum, irrespective of wave-forms. In a recent paper* I showed that for mumetal and permalloy laminations of about 0·015 in. the same relationship holds for frequencies up to about 25 cycles per sec. and at higher frequencies when the flux density is approaching saturation. With magnetizing forces of the order that give maximum permeability with direct current it is found that the flux density at, say, 50 cycles per sec. is only a small fraction of the value obtained with the corresponding d.c. magnetizing force. It was at first thought that this discrepancy could be accounted for by taking the magnetizing force as $H \sin \theta$, as shown in Fig. 8. Curiously, the steep portion of the curve obtained by plotting $B_{max.}$ against $H_{max.} \sin \theta$ did agree reasonably well with that plotted from d.c. results; but with higher magnetizing forces the difference became greater and greater—as may be gathered from the steepness of the upper portion of the $H \sin \theta$ curve in Fig. 8—whereas the experimental results in this region showed a good agreement between the d.c. and the a.c. values based upon the total magnetizing force. In other words, there is no justification for taking the reactive component of the current as the magnetizing component.

In my paper I showed that the E/H and the B/H loops for mumetal and permalloy were asymmetric over a certain range of magnetizing force. Since the publication of that paper Mr. T. A. Ledward, of Liverpool, has found that the asymmetry is due to polarization of the innermost portion of the lamination and that it can be eliminated by applying a very large magnetizing force and reducing the latter relatively slowly. He has also found that it is possible to have a 0·015-in. lamination polarized simultaneously in one direction at the centre and in the opposite direction near the surface.

I shall be very interested to know how the author calculated the flux density from the test results obtained with the Heaviside inductance bridge. In the paper referred to above, I pointed out that, for nickel-iron specimens, there may be considerable error if the flux density is calculated from the flux linkages per ampere of the equivalent inductance deduced from a bridge test.

Dr. E. Wassell Smith: I propose to say a few words on the loading of submarine cables with mumetal.

I do not think it is generally realized that the requirements in regard to the loading material have considerably changed since the introduction even of the loaded cable. In 1924 the chief object was to get as high a permeability as possible, as the author mentions; but it was later realized that the serious limitation of these continuously and completely loaded cables was the fact that they could not be duplexed. Owing to the variation of the properties of the magnetic material with current, and to irregularities over the length, it was not possible to design a network whereby a duplex balance could be made. Consequently, just prior to 1926, the metal requirements were changed. It was decided to put unloaded ends on a loaded cable, extending for 100 miles or so along the cable, and then to graduate the inductance from a low value, where those unloaded portions ended, to a high value in the centre of the cable. Consequently it became a problem for the metallurgist to control the permeability of the mumetal from about 2 000 to about 6 000. It says much for the versatility of this metal under various heat treatments that this aim was realized, and in two cables laid in 1928 and 1930 respectively a permeability range of from 2 000 to 6 000 was obtained. Impedance/frequency tests taken on the laid cables showed only the main reflection due to the junction between the loaded and the unloaded cable; there were no minor reflections due to imperfections in grading.

---

* "Magnetic Characteristics of Nickel-Iron Alloys with Alternating Magnetizing Forces," *Journal I.E.E.* 1936, vol. 79, p. 213.

With regard to the losses in mumetal, in the average submarine cable the eddy-current loss accounts for between 5 and 10 per cent of the whole attenuation, the hysteresis loss for about 3 per cent, and the after-effect loss for less than 1 per cent. In this connection I should like to ask whether the author sees any chance of giving us an improved type of mumetal having a higher resistivity.

The Sumpner-galvanometer test method has been recently improved, and gives consistent and reliable results. Another test method mentioned in the paper uses a vibration galvanometer; I know this instrument is exceedingly sensitive, but the mirror is very small and it is tiring to watch and gauge the width of the dim band of light reflected from it. I prefer a sensitive rectifier voltmeter or a thermionic voltmeter as a detector. Regarding bridge testing, the ordinary bridge is applicable only under two conditions. One is that it must allow of the convenient application of a polarizing field, and the other that it must not distort the sinusoidal voltage with which it is generally (though not universally) desired to conduct the test. I do not think the Heaviside bridge is particularly good from either of these points of view. The secondary winding is always in circuit and the sinusoidal-voltage requirement is thereby upset. Further, the polarizing field is broken every time an adjustment is made. I have used both the Owens and the Hay bridge, but have concluded that the best type is a simple Maxwell bridge in which the ratio arm adjacent to the test specimen has a resistance not exceeding 1 ohm.

Mr. P. Beringer: Referring to Fig. 4, it would be of very great interest if curves for a few intermediate values between (*b*) and (*c*) could be given.

I occasionally unwind heat-treated mumetal clockspring cores and rewind them to a different diameter. In some cases I find that the deformation does not seriously affect the permeability and that the B/H curve over the working range is still approximately as shown in Fig. 5(*a*), even though the heat-treatment has not been repeated.

Mr. F. E. J. Ockenden: It is now some 12 years since I first employed a nickel-iron transformer core: it was made of permalloy and was of the clockspring pattern. The use of nickel-iron alloys for transformer cores developed rapidly at that period, and current transformers were produced having errors so small as to be undetectable by the average transformer testing equipment of that time. More recent advances in testing methods, such as those developed by Dr. A. H. M. Arnold at the N.P.L., now enable the most precise tests to be made on current transformers even when the phase-displacement error is only a few tenths of a minute. I do not entirely agree with Mr. Buchanan about the effect of varnish on the interleaving of the mumetal. If one takes a clockspring coil and endeavours to decrease the eddy-current losses by soaking it in wax the external volume of the core is not altered. Consequently, one cannot say that the gap between the interleavings of the core has been increased. Nevertheless, the permeability of the core decreases by a small but definite quantity, and it would appear that this is due to the constraint imposed on the turns of the coil by the setting of the wax or drying of the varnish, and not to increase in the separation between adjacent layers.

With regard to the stability of nickel-iron components, one of the first nickel-iron instruments which I constructed (in 1927*) has been re-tested at intervals ever since and no change from the original calibration has been detected. This is a great testimony to the reliability of the mumetal, even as made 10 years ago.

A problem which is not mentioned in the paper, but which I think is of interest, is that of finding some method of discriminating between the various nickel-iron alloys employed in practice. I understand that where the percentage of iron is less than 50 a test with copper sulphate fails to deposit copper on the material, but it would be useful to have a more precise test if such is available.

An advantageous feature of mumetal is the simplicity of its core-loss and magnetization curves. In dealing with current-transformer design it is at times particularly helpful to be able to make a mental estimate of the foregoing quantities for any given flux density, and whereas with silicon steels the curves are too complicated to carry in one's head, the "straight line" characteristic of mumetal makes it comparatively easy to do so for this material.

As regards hydrogen annealing, I noticed the other day a statement to the effect that where metals are concerned, hydrogen must be treated as an alloying element: thus it would appear that if mumetal be annealed in hydrogen, the hydrogen will alloy with the metal and produce a material which may have unstable characteristics owing to the volatile nature of the hydrogen. It is possible that this is the explanation of the author's statement that hydrogen annealing is likely to be unsatisfactory.

I cannot agree with previous speakers or even with the author himself, when they deprecate the value of a.c. permeability and loss curves. In current-transformer design one has to know the effective a.c. losses and the a.c. permeability, and, in spite of their greater academic accuracy, d.c. values are not as helpful. It has been shown that, for the low values of H obtaining in current transformers, the magnetizing current may be considered substantially sinusoidal; the use of B/H curves based on a.c. values of B and H is thus not as illogical as would at first appear, and offers considerable advantages to the designer.

---

* See K. EDGCUMBE and F. E. J. OCKENDEN: *Journal I.E.E.*, 1927, vol. 65, p. 553.

Dr. A. B. Everest: With regard to the theories set out on page 650, I am inclined to agree that strain is the underlying factor in regard to the properties of high-permeability nickel-iron alloys, and this seems to me a logical conclusion, seeing that one gets the highest permeability with the lowest hysteresis losses and that also at very nearly the same composition one gets the minimum magnetostriction.

The author mentions that one of the limitations of nickel-iron alloys is their low saturation value, and a case on which this has a bearing is that of solenoids for operating electric organs. Would it not be possible, in cases of this sort, to employ armatures having composite cores, in which the high-permeability alloy would be interleaved with a material of a higher saturation, such as pure iron? By this means it would appear possible to combine the advantage of the quick response of the nickel-iron alloy with the greater power available as a result of the higher saturation value of the pure iron.

Finally, although the author has indicated that he is not prepared to discuss nickel-iron alloys in powder form, is it not possible that this subject might be of interest in relation to instruments where powder cores might with advantage be employed. A direction in which attention is being given to this subject to-day is in the development of cores made up from powder with a suitable binder such as bakelite, with the result that the core can be formed by moulding.

Mr. G. A. V. Sowter: In spite of its widespread use I do not think it is generally appreciated that mumetal is not saturated in the earth's field. A series of letters by Dr. E. Hughes, Dr. Spooner, and myself, have been published* and indicate how small is the influence of this field upon the properties of the alloy. At the Physical Society's Exhibition of about 2 or 3 years ago I gave a demonstration in which a mumetal rod fitted with a search coil and connected to a galvanometer was reversed in the earth's field to give a resultant change of flux density of only a few lines per cm². Also, some tests here made by E. W. Smith and H. S. Craig, first of all in the earth's field and then with the earth's field carefully neutralized, show variations in magnetic properties of only 1 or 2 per cent.

In connection with intervalve transformers on factory test, most radio manufacturers adopt the method of measuring the current and the voltage-drop across the primary winding to determine the impedance, but consider this to be wholly reactive for the deduction of inductance. Large errors can arise in this method with mumetal cores, owing to the fact that in this case the magnetizing current and the loss current are comparable, whereas with silicon iron the former current greatly exceeds the latter.

Turning to the question of shielding, we have found in practice that in a small mumetal box the effects of joints are much less than in a large one. Thus a box approximately 1 cub. in. in volume may show a reduction of 50 db. at 50 cycles per sec. whilst a box made from the same material but of 8 cub. in. volume will only show a reduction of 30 db.

In connection with the relative merits of a.c. and d.c. tests, I find that it is possible to get quite close correlation between an experimental d.c. curve and one derived from an a.c. test, except in the region of maximum permeability.

With regard to a.c. testing, originally one used the wattmeter method, but this has been superseded by the Heaviside equal-ratio bridge. Although this involves relatively high resistances in series with the wound core under test, the form-factor variations are not serious and results only differ towards saturation, where they may vary by 10 per cent from values obtained on a Maxwell bridge.

On one occasion I found some years ago that the measured losses of nine current-transformer cores tested as a single core were about 20 per cent worse than the summation of the results of the individual tests. I came to the conclusion that this was due to the extra eddy-current losses arising from the fact that the nine cores were piled on top of each other. On putting rings of insulating material between cores the loss was reduced by approximately 20 per cent. This experiment showed us the necessity for using narrow strip for spiral cores.

In connection with hysteresis loops, when the recent paper by Dr. Hughes* appeared I was surprised to find his assertion that the hysteresis loop of metal was asymmetric, as this was in conflict with some results I had obtained from experiments carried out in 1924. Dr. Hughes has indicated to me, however, that the asymmetric loop is only obtained when one uses mumetal without a gap. I am pleased to say that I have since found this to be the case; I will now show the asymmetric loop and reverse it, to confirm that he has discovered what I call the "Hughes effect." (Mr. Sowter here gave a practical demonstration of the effect.)

Another question which is frequently asked is: Does over-magnetization do any permanent damage to mumetal? I contend that the original properties of the material can always be restored by subsequent treatment. It is rather more difficult to demagnetize ring samples without a gap than ordinary laminations, but it is always possible, although the methods of demagnetization are by no means perfect. The ordinary method of slowing down an alternator seems to give very good results, although commercially a potential-divider method is employed.

What is the effect of temperature on mumetal? An increase of temperature up to 100° C. improves the properties of the material at that temperature, and there is little permanent effect even when the material is raised to temperatures such as are employed for the bakelizing process.

We supply many mumetal current-transformer cores which are taped and waxed, and, as Mr. Ockenden pointed out, this causes a slight reduction in the magnetic permeability. It is stated officially that the reduction may be up to 10 per cent, but it is not usually so large as this.

In connection with ageing, for the mumetal used in the loading of laid submarine cables the change in permeability during a number of years has only been 1 or 2 per cent. Also, one Government Department uses a mumetal core with two windings as a standard, and ageing has only produced in this a change of about 1 per cent. Further, mumetal has been used in relays subject to constant vibration day and night for 5 years, and they have shown no appreciable change in performance during this period. In contrast to this, silicon iron shows pronounced ageing effects.

---

* *Electrician*, 1934, vol. 113, p. 463.

* *Journal I.E.E.*, 1936, vol. 79, p. 213.

I should like to say that, so far as I know, H. S. Craig first thought of the clockspring type of current-transformer core a few years ago, and endeavoured to obtain a patent for it. The same idea had occurred about 1880 to a Russian engineer, who obtained a patent for it, and stated the merits of paper interleaving and narrow strip for the reduction of losses—a truly remarkable performance for that period.

Mr. P. W. Willans: I am interested in the paper primarily as a user of nickel-iron alloys in transformers and chokes for telephonic frequencies, and while I am in no doubt whatever as to the excellence of the results obtainable with these alloys on high-grade apparatus, I feel it is somewhat dangerous to claim, for example, that a mumetal transformer can always be advantageously used in place of a silicon-steel transformer, even at flux densities where saturation does not enter into the problem. A radio manufacturer is accustomed to design an iron-cored transformer so as to give a definite loss at low frequencies, say 3 db. at 100 cycles per sec., such a loss being considered tolerable under practical conditions. In such circumstances, not only the value but the quality, so to speak, of the inductance comes into question, and it would appear that the variation of permeability with amplitude is an important factor. If, owing to such variation, a variable low-frequency attenuation occurs at different signal amplitudes, there must necessarily be amplitude distortion and production of harmonics. It is my experience that nickel-iron alloys are worse in this respect than silicon-steel, and that in consequence it is necessary to design for a higher inductance value when using them. If one can attain conditions where the low-frequency attenuation is negligible, the results obtained by the use of mumetal are exceedingly good. I would add, in this connection, that this material can be used to great advantage in the design of chokes carrying substantial polarizing current, an air-gap of suitable length being employed. In a small choke built up on stampings weighing 11 oz. an inductance of 700 henrys can be obtained when a current of 5 milliamps. is flowing through the windings. Such a choke, used in conjunction with a screened tetrode or pentode, enables a voltage amplification of 200 to 300 to be obtained at frequencies from 40 to 10 000 cycles per sec. with negligible frequency distortion. An amplifier embodying two such stages and giving a gain of 90 to 100 db. is a very useful laboratory instrument.

I am interested to know whether curve (*b*) in Fig. 5 corresponds to a core having interleaved or butted joints. My surmise is that the joints are interleaved, as there appears to be no substantial difference between curves (*a*) and (*b*) in the region of low flux density, and my experience is that there is a definite loss, relative to an interleaved core, when the joints are butted.

With regard to the preparation of data, I appreciate that there are so many applications of the materials described in the paper that some limits must be set to the manner in which their magnetic characteristics are set out. I nevertheless venture to make a few observations and requests from the standpoint of the class of user to which I belong. First, our principal requirement is in relation to figures of initial permeability (i.e. corresponding to the very lowest value of alternating flux density both with and without polarization of the core), since if a transformer or choke gives negligible low-frequency attenuation at the lowest values it must do so also at the higher values until saturation is attained. Secondly, in the case of a polarized core we are interested to know the permeability in relation to the steady flux density in the core and not in relation to the magnetizing force producing this flux density. If the results are furnished in the latter form it is necessary to convert them to the former in order that they may be applied to the design of cores having air-gaps, since the magnetizing force to produce a given flux density is, of course, totally different when there is an air-gap. In this connection I should like to draw the author's attention to a paper by Dr. R. T. Beatty* giving an excellent graphical method of exhibiting the results obtained from B/H and initial-permeability measurements in a manner which greatly facilitates the design of such cores. I should welcome the provision of data in this form.

Lastly, I should like to point out that when chokes carrying polarizing currents are used in practical telephonic-frequency apparatus the magnetic condition of the cores is arrived at as a result of a series of makes and breaks in the circuit when the apparatus is switched on and off. The transition is thus, not from a given polarizing current to the reverse value, but from this current to zero. A B/H curve plotted from data corresponding to make and break, and not to reversal, might turn out to be substantially different from that ordinarily published and, if so, it is the curve we want.

Mr. J. G. Story: I am interested in the application of high-permeability alloys to the design of audio-frequency transformers.

Audio-frequency transformers can roughly be divided into two classes—those working between low impedances, and those working between high impedances. Whereas in the first class the reduction of leakage reactance is, of course, important, in the second class the reduction of effective winding capacitance is often more important, especially when the transformer is working into a tetrode or pentode valve. It is obvious that high-permeability alloys aid the design of the transformer working between low impedances but it is not, perhaps, so apparent that as the permeability of the core is raised the effective winding capacitance is, in general, reduced. I have usually found that the smaller the core adopted, the less is the effective winding capacitance; and, of course, high-permeability materials permit, within limits, the adoption of a smaller core size. In audio-frequency transformers one serious limitation to the reduction of the core size is, as Mr. Willans has said, the harmonic distortion that may be introduced by these high-permeability alloys.

I have recently made a number of measurements of the harmonic distortion introduced by interleaved transformer cores of various materials at a frequency of

---

* *Wireless Engineer*, 1934, vol. 11, p. 61.

50 cycles per sec. As an illustration of the limitations of the high-permeability alloys in this respect I found, for instance, that, when the primary reactance was made equal to 4 times the combined referred load and source resistance, for a total of 1 per cent harmonic distortion (on a voltage basis) " radio metal " could be worked at a maximum flux density of about 1 000 gauss, mumetal at 2 500 gauss, and permalloy C at 2 000 gauss; whereas ordinary stalloy could be worked at 4 000 gauss and a special stalloy can be obtained which will stand 6 000 gauss for the same percentage harmonic. For a total of 2 per cent harmonic the relative order of mumetal and radio metal is reversed, radio metal allowing a maximum flux density of about 6 000 gauss and mumetal about 3 500 gauss.

A further limitation to the reduction of the core size is the drop in the effective permeability. I should like to ask the author how much of this drop is due to metallurgical reasons, and whether the structure of the material, and therefore the permeability, is upset near the edges of the stampings owing to shearing strains. If this is the case, to what depth is the permeability impaired?

Dr. W. G. Radley: On page 658 the author gives some figures showing the improvement on the " on " and " off " current ratio of polarized relays which can be obtained by replacing the iron cores by mumetal cores. The improvement follows from the much smaller magnetizing force required to reverse the flux in the mumetal core. Many polarized telegraph relays are in operation with such cores. Most telephone relays are not made of mumetal, for the reason the author mentions, namely that they have to deal with large quantities of energy. Release of such relays is brought about by a spring load on collapse or reduction of the flux. At many points in a modern telephone circuit such relays have to respond to, and repeat, trains of signalling impulses. The greater the difference between the current required to operate the relay and that just allowing it to release, the greater is the difficulty of repeating such a train without distorting the length of individual impulses. Has the author figures for non-polarized relays corresponding to those given on page 658?

Mr. A. J. Gibbons: I have one question to put in connection with the effect on mumetal current transformers of heavy magnetization such as may be produced by currents up to 40 or 50 times the normal full-load primary value, which have a strong d.c. component. Such a current will be interrupted by an oil circuit-breaker at or about zero value. What will be the effect of this very drastic treatment, over which we have no control whatever, on the losses of the mumetal core? I am prepared to agree at once that the losses normally are so small that even a considerable increase would not materially affect the performance of the current transformer.

Mr. G. W. Elmen (U.S.A.) (*communicated*): The paper under discussion is further evidence of the importance of the high-permeability iron-nickel alloys as magnetic materials. It covers a considerable amount of ground historically and with implications with which I am not always in agreement. In particular, there is not brought out the failure of the early investigators to explore the low-flux-density region, and their lack of interest in it. In that connection pertinent references will be found in a recent American I.E.E. paper[*] and its discussion.[†]

The author's experience in the production of mumetal is along the same lines as that of others who have been concerned in the development of iron-nickel alloys for magnetic use and in their quantity production on a commercial scale. In some instances methods other than those described in the paper have been found more advantageous; for example, these alloys have been produced satisfactorily on a commercial scale by melting both in the low-frequency induction furnace and in the arc furnace.

As a laboratory tool the small high-frequency furnace is invaluable, but it would not be correct to say that it made the investigation of these alloys possible. In fact, that type of furnace was not available when I began my own investigation of these alloys in 1913. The permalloy alloys, which gave the first indication of extremely high permeabilities, were produced by the then prevailing commercial melting technique.

In analysing the magnetic data in the paper I find myself handicapped by the lack of definite statements of the compositions used. It would seem from the patent references that the mumetal discussed is a nickel-iron alloy containing between 70 and 80 per cent nickel and a few per cent copper. My experience with these alloys is that such an addition of copper increases the resistivity but slightly, and has little effect on the magnetic characteristics except for a gradual decrease in the saturation induction with the increase in the copper content. The resistivity of about 50 microhm per cm. cube, which the author mentions for the alloy discussed in the paper, is the same as I obtained by adding 2 per cent chromium to 78·5-permalloy (see American I.E.E. paper quoted above).

The statement that the extremely high permeability is decreased when the permalloy is modified by the addition of other metals, must not be accepted without reservations; for example, 3·8–78·5 Mo-permalloy develops an initial permeability of about 20 000 with ordinary commercial control, as compared with 10 000 for 78·5-permalloy quenched at the proper cooling rate from 600° C. (not by " slow cooling," as stated on page 651).

The curves in Fig. 1 are vivid illustrations of the importance of prior mechanical and heat treatment on the final qualities of a magnetic alloy. In addition, the effects of rolling direction, and of mechanical distortion and strain, on the final heat-treated core properties are noteworthy, and typical of alloys of the permalloy type.

The numerous conditions which must be satisfied in the production of high-permeability iron-nickel alloys would seem to indicate that they are difficult to handle on a large commercial scale. Comparatively speaking, the reverse is the case, for these alloys are produced with rather large latitude in composition, and particularly in impurity content. To produce permeabilities of the same order in iron (and this can now be done in the laboratory) extreme care must be taken to eliminate traces of impurities which need not be considered in the production of the permalloys.

Dr. E. P. Harrison (*communicated*): With regard to the question of "purity" and the effect of hydrogen in particular, it appears to be the general view at the moment that the striking improvement in permeability effected by heating in this gas is not to be completely explained as a result of chemical reduction of undesirable traces of "impurity." There seems to be evidence that hydrogen in small quantities modifies the fundamental characteristics of the alloy.* In any case, important information might well be obtained by using an atmosphere of hydrogen *during the melt itself* in the induction furnace. It is well recognized, I believe, that a hydrogen atmosphere during the annealings following each stage of hot drawing (in the case of wire production) has proved to be essential in giving to the alloy the highest permeability after the final appropriate heat-treatment.

---

[*] *Electrical Engineering*, 1935, vol. 54, p. 1292.

[†] *Ibid.*, 1936, vol. 55, p. 887.

Some interesting results connected with these alloys involve the effect of passing audio-frequency alternating current through a wire of the material. If, for instance, a No. 36 S.W.G. wire, 15 cm. long, of high-permeability mumetal, is supplied with alternating current at 500 cycles per sec., a change of 20 per cent in its effective resistance is caused by simply rotating it in a horizontal plane through 90° in the earth's magnetic field.† This is a skin-effect phenomenon the theory of which is much complicated by the fact that the permeability cannot be regarded as even approximately constant over the cross-section of the wire.

As regards the effect of strain on hysteresis, I have found that if a wire (No. 26 S.W.G.) of the alloy is subjected to a tension of about 276 kg. per cm^2 (1 lb. weight on the wire), and if at the same time the wire carries 17 milliamps. alternating current, the B/H curve shows zero measurable hysteresis. The maximum field values in the case which I investigated were $\pm 0 \cdot 5$ c.g.s., so that the measurements were carried well beyond the shoulder of the loop.

The paper raises several very interesting points, one of which is the consideration of the zero-magnetostriction composition in its relation to the maximum-permeability composition which the author discusses on page 650.

Mr. H. Horwood (*communicated*): I am rather interested to find that certain unorthodox theories put forward by me in a semi-metaphysical paper‡ written about two years ago, are somewhat confirmed by the present author's findings. Molecular "ordering," crystal orientation, and grain orientation effected by rolling, mentioned by him, remind me of some of the unusual remarks I then gave vent to, e.g. ". . . the scattered unorganized atoms are marshalled together in a certain order." "When magnetized to saturation every possible atom is mobilized and lined up."

In this connection Fig. 4 in the paper is especially interesting. The variation of permeability with rolling direction seems to depend upon the cosine of the angle between the flux and the rolling direction. Thus at 60° one would expect the curve to reach a maximum of about 3 000, and it would be useful if the author could give some actual figures obtained at other angles, as already suggested by Mr. Beringer.

Mr. W. F. Randall (*in reply*): I wish to thank those who contributed to the discussion for raising matters consideration of which has opened up new points of view upon unsolved problems relating to high-permeability alloys.

I agree with Mr. Webb that the most important factor influencing development of high magnetic permeability appears to be the elimination of mechanical and magnetostrictive stresses; but, in the operation of this factor, grain orientation must play a very important part, for magnetostriction varies with the direction in which the crystal is magnetized. Magnetization during the cooling period of the heat-treatment cycle facilitates the establishment of stress equilibrium by creating stresses at a stage when the plasticity and molecular activity are high and sufficient for the metal to adjust itself to a strain-free, magnetized, condition. The fact that iron does not respond to this magnetic treatment may be due to the wide variation, in weak fields, of magnetostriction effects with increasing magnetizing forces in that metal. In the nickel-iron alloys magnetostriction is fairly constant or increases at a steady slow rate, whereas in iron the effect at first increases rapidly and after reaching a maximum falls away again to negative values. In consequence there is a greater variation of stress when magnetization is effected in iron, and a magnetizing force of fixed magnitude would not so easily achieve the essential strain-free condition. The reduction of hysteresis by compensating stress, illustrated by Dr. Harrison's experiment, lends support to the theory proposed, for low hysteresis is closely associated with magnetic softness and high permeability.

Mr. Buchanan suggests grading of mumetal to meet a commercial need. This is already done to some extent and, if the demand is sufficient, co-operation with designers to formulate such specifications will be welcomed.

The improvement due to straightforward hydrogen annealing may be put down mainly to the release of strain, consequent upon the reduction and removal of inclusions. Such effects are as permanent as those produced by ordinary heat treatment, but the results obtained by Cioffi (referred to by Mr. Ockenden and Dr. Harrison) cannot be explained on this basis, as special temperatures and gas pressures are essential to develop the extremely high permeabilities obtained. These figures are most easily explained on the assumption that the gas is alloyed (or occluded, which appears to be a similar condition) with the metal, and in such cases the high permeability is readily destroyed. Dr. Harrison's proposal to subject the metal itself to hydrogen treatment during melting would therefore only be valuable for the purifying action, as the hydrogen "alloy," requiring definite temperature-pressure conditions for its formation, would be destroyed or could not be formed in the melting process. The advantages of this method of melting have been realized but practical application is not easy.

The investigations carried out by Von Auwers and Neumann (mentioned by Mr. Webb) are a most valuable contribution to the study of high-permeability alloys. Alloy "1040" was developed from this work, and I believe that its manufacture demands a more specialized technique in melting and working than does mumetal. As far as I know it is not yet available commercially.

---

* J. C. CHASTON: "Permalloys and Related Ferromagnetic Alloys," *Electrical Communication*, 1936, vol. 15, p. 38.

† E. P. HARRISON, G. L. TURNEY, H. ROWE, and H. GOLLOP: *Proceedings of the Royal Society*, 1936, vol. 157, p. 451.

‡ "Matter, Electricity, and other Material Phenomena," *Electrical Supervisor*, 1935, vol. 15, p. 273.

The basis of both "1040" and mumetal is the addition of copper (about 5 % in the case of mumetal and a considerably higher proportion in the case of "1040") to a nickel-iron alloy, and, as Mr. Elmen points out, this addition causes a proportionate decrease in the saturation induction. The advantage found in the case of mumetal is that the resultant alloy is less susceptible to heat-treatment variations, and high permeability can be developed by an ordinary annealing process.

Messrs. Buchanan and Beringer raise questions relevant to Fig. 4. Owing to the fact that initial permeability is generally of greatest importance in commercial applications, rolling procedure is adjusted to achieve the highest value of μ_0 in accordance with the requirements shown in Fig. 1. In agreement with this, at 45° to the rolling direction μ_0 has a value which is the average of its values parallel to and at right angles to that direction (Fig. 4); but, as H increases, the variation of μ with grain orientation (as determined by rolling) alters, and this may explain why μ_{max} at 45° is not also a corresponding average value.

Fig. 14 is plotted from observed results. The slight rise in incremental permeability is definitely shown, and the phenomenon becomes more evident as the frequency is increased. The reason is not easy to see.

The drastic treatment which Mr. Gibbons proposes to give the current-transformer cores would have a small temporary effect on both ratio and phase-angle errors, but the original condition of the core would be restored by simple demagnetization.

Dr. Hughes's remarks are of great interest. At present it appears that our knowledge of magnetic phenomena is insufficient for us to obtain complete concordance of d.c. and a.c. magnetization curves, or to deduce a.c. behaviour accurately from d.c. data. Fig. 8, however, although possibly at fault basically, enables us to gauge a.c. performance and to design accordingly.

A higher-resistivity alloy for cable loading is required by Dr. Smith. Resistivity can be increased readily, but unfortunately this is accompanied, according to our present knowledge, by a decrease in permeability.

Dr. Everest suggests that composite cores of nickel-iron alloy and pure iron would be advantageous in certain applications. This principle, in which a nickel-iron tube encloses a soft-iron core, has in fact already been applied to telephone relays. In connection with the figures given on page 657 relating to radio transformer cores, the weight of a silicon iron core to give equivalent inductance is about $1\frac{1}{2}$ lb. I regret that the figures for non-polarized relays required by Dr. Radley are not available.

In reply to Mr. Willans's remarks, I am appending a curve showing (Fig. C) incremental permeability as a function of induction, and wish to thank him for his suggestions as to the way in which magnetic data are most conveniently presented. The other data required appear in the published booklets.

Mr. Story says that he has noted a falling-off in effective permeability with reduction of core size. I know of no metallurgical reason to account for this, and suggest that it may be due to the greater proportionate effects of the joints in small stamping assemblies. Laminations are of course heat-treated after stamping, so that the effect of the sheared edges is eliminated. The effect of a simple shearing operation would hardly be noticeable on heat-treated strip if it were certain that no bending or distortion of the metal had been occasioned by the operation, but it is very difficult to ensure this in practice.

The magnetic "stratification" of worked mumetal indicated by the results quoted by Dr. Hughes and Dr. Harrison has been observed, but is not yet explained or fully investigated. The phenomenon is, however, more pronounced as the section becomes thinner and the frequency higher. The explanation of the variation of permeability shown in Fig. 3 may not be quite so simple as that given in the text, for the curve as drawn applies to 50-cycle conditions, and the shape is very different at higher frequencies. This is illustrated by the change-over of the B/H curves shown by comparing Fig. 12 (50 cycles) with Fig. 13 (2 500 cycles).

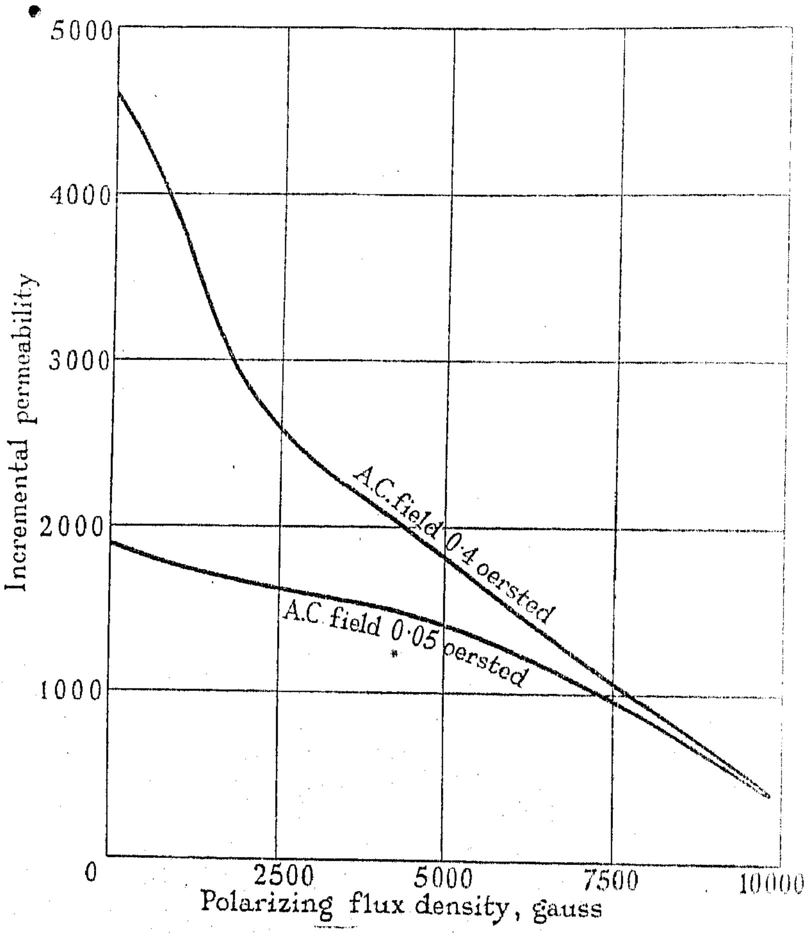


Fig. C.—Incremental-permeability curves for radio metal, obtained at 50 cycles per sec. with polarizing flux density.

In the discussion questions were asked about the saturation induction of nickel-iron alloys. This property of magnetic materials is a physical constant determined, according to the latest hypotheses, by the constitution of the atom, so that its value is unlikely to be altered or controlled by comparatively simple processes such as adjustment of grain orientation or heat-treatment, which have, as shown, a very considerable effect upon crystal structure and permeability. If higher saturations are required in combination with high permeability, the problem will most likely be solved by the development of high permeabilities in alloys which are already known to have high saturation induction.

Mr. Ockenden calls for a test discriminating between various nickel-iron alloys. I know of no rapid method other than that mentioned, and for closer identification it would be necessary to resort to chemical analysis.

Mr. Elmen's pioneer work on the magnetic properties of nickel-iron alloys at low flux densities makes his remarks of particular interest. In my own experience it is difficult to ensure production of a consistent high-quality material by arc-furnace melting, and it is noteworthy that these alloys have been produced satisfactorily by that means. I agree, nevertheless, with Mr. Elmen's statement that nickel-iron alloys are less difficult to manufacture than is iron of similar permeability. The latter product demands very specialized methods which are hardly beyond the laboratory stage, but in my paper I have compared the methods of production of nickel-iron alloys with standard methods employed in metallurgical practice and, judged by this standard, Mr. Elmen will agree that nickel-iron alloys require a much greater and stricter degree of control.

DISCUSSION ON
"THE ELECTRICAL CHARACTERISTICS OF 132-kV LINE INSULATORS UNDER VARIOUS WEATHER CONDITIONS"*

WESTERN CENTRE, AT CARDIFF, 8TH FEBRUARY, 1937

Mr. C. T. Allan: I should like to ask why suspension insulators are less satisfactory when used as such, namely in a vertical string, than when operated as tension insulators in a more or less horizontal position. One would have expected the reverse to be the case, because in the horizontal position the insulators would be more liable to be wetted on both sides.

I am interested in the revival of the oil-filled insulator, and I am prompted to ask whether, after some time in service, creepage of the oil over the insulator surface does not result in that surface being covered with dust, insects, thistledown, etc., as used to be the case; and whether this does not result in a flashover or breakdown of the insulator.

Mr. J. B. J. Higham: There are two questions I should like to ask the author. First, would the removal of the metal shields from the oil type of insulator affect the electrical characteristics to any great extent? Second, in what way is the potential gradient on a string of insulators affected by dirt-deposit and fog conditions? Does the potential across the string tend to become equally divided, or does the change of impedance with change of potential on each unit tend to cause unstable conditions?

Mr. G. H. Bowden: My experience in testing high-voltage outdoor insulators has been limited to the taking of dry- and wet-sparkover voltages of post- and pin-type insulators, and the paper shows me that, since I was last engaged in that type of work, the technique of testing has developed considerably.

In testing, irregular or peaky voltages have appreciable effect in bringing about the breakdown of air insulation. Anyone who has witnessed either insulator tests or insulator operation under adverse climatic conditions must realize that high-frequency voltages are very evident. I would ask the author whether these high-frequency voltages have been found to have appreciable effect in his tests. If the testing supply had appreciable line-to-earth capacitance, such as would be the case if the strings under test were connected to an overhead line, would the test results be appreciably altered? It appears to me that, if the insulator discharge had any tendency to generate high-frequency voltages, the high-frequency impedance of the testing supply shown in Fig. 4 would choke any high-frequency current tending to flow between the units of the string under test.

Under fog conditions that lead to dirt being deposited on the insulator surface, is the mechanism of breakdown of the insulator chain a sort of train effect, one unit breaking down after the other until the whole string flashes over? Further, is it the arc which passes over the insulator surface that flashes over, or does the insulator surface-discharge so ionize the air surrounding the insulator that the new arc forming the actual flashover is permitted to pass?

I note that the leakage current is taken from the bottom insulator but one, and the cap-to-pin capacitance of this insulator, together with the core-to-sheath capacitance of the test leads, will tend to bypass any high-frequency current from the testing instruments. The order of these capacitances would be interesting information, as would also oscillograph records of the voltages applying—on a time-base which would show accentuated the irregularities occurring in the applied voltages.

Mr. G. E. Whitehead: Some few years ago Mr. Arthur Ellis was interested in the problem of grime and salt deposit on overhead-line insulators, and at his suggestion I had a string of shed insulators rigged up, under which for some months garden refuse was burnt with a view to ascertaining the effectiveness of a simple device that I was anxious to try out for preventing settlement of deposits. The device took the form of a brush windmill composed of bristles such as are utilized for cleaning small bottles, on a light cane frame foundation. The bristles of the central ring acted as spacers, and three vanes were arranged at a suitable angle for rotation by the wind (these were very light and did not affect the glazing). Sufficient intermittent movement apparently took place at intervals, but during bad weather the action of wind and rain ensured a perfectly clean surface except for those parts not operated on, where the grime deposit was more or less solid. In gusty weather two of these devices reached the higher insulator and thoroughly cleansed the corrugated under-side.

---

* Paper by Mr. J. S. Forrest (see vol. 79, p. 401).

The point of interest was whether the disadvantage of the device on the smooth upper plain surface of the insulator would be more than compensated for by the clean condition of the insulator generally. Behind the experiment was the somewhat vague idea that the necessity of ascending towers to clean insulators could be avoided at the probable cost of, say, 2d. per insulator, estimating the life of the device at 2 years.

Although this experiment was not intended as a serious contribution to the problem, and the patents were allowed to lapse, it was very interesting some 2 years afterwards to find that the identical device, evidently made from the patent drawing, but of German origin, had been sent to an engineering firm in this country as a sample.

Mr. W. Hill: I should like to know the capacity of the author's testing transformer. I believe that, unless the transformer is big enough to maintain the voltage with heavy leakage currents, very distorted readings may be obtained. Similarly I should like to know more about the selection of the test voltage, because I do not think one can make tests at a single voltage and get comparative results by a simple proportion sum. When experimenting on anti-salt insulators we certainly had a good deal of difficulty arising from both the above points.

I should also ask whether any investigation has been made of the field round the insulator. In the design of anti-salt insulators which have proved satisfactory over many years and through many salt storms, we found the most important factor was investigation of the field. I suggest that the field round the insulator may play an important part in the explanation of the different results obtained on suspension and on end strain strings of insulators.

Mr. Horace G. Weaver: I should like to ask the author whether any material other than porcelain has been tried or suggested for making these insulators.

Mr. J. S. Forrest (*in reply*): In reply to Mr. Allan, the superiority of tension strings over suspension strings of similar units appears to be due to the fact that both sides of the tension insulators are subjected to the cleaning action of wind and rain. A clean porcelain surface is quite a good insulator even when wetted, while a soiled porcelain surface is a very poor insulator in a humid atmosphere even if it is not directly exposed to rain. In addition, it is possible that in the case of tension insulators there is less tendency for the leakage-current surges to develop into complete flashovers.

With regard to oil-filled insulators, creepage of the oil over the outer surface does occur after several months, with the result that foreign bodies become attached to the insulator surface. This does not appear to be detrimental, however, as the performance of the insulator remains satisfactory.

In reply to Mr. Higham, it is not considered that the removal of the metal shields from the oil-filled insulators would affect the electrical characteristics to any great extent. Although the metal shields tend to make the capacitance grading more uniform, the potential distribution along the string under humid conditions is determined mainly by the leakage over the insulator units. Under foggy or even humid conditions, the potential distribution along a string of insulators becomes much less uniform than under dry weather conditions. The mechanism of this phenomenon appears to be as follows: Under dry weather conditions, although the voltage distribution along a string is fairly uniform, the potential-drops across all units are not exactly the same. Now, as shown in the paper, under humid conditions the impedance of a porcelain insulator increases as the applied voltage increases. In damp weather, therefore, the units having the smallest potential-drop tend to have a lower impedance than the other units in the string. Consequently, the voltage across the former units decreases still further, and as a result the excess voltage is applied to the latter units, thus increasing their impedance and in turn the voltage-drop across them. The potential distribution is accordingly unstable under humid conditions, and the ultimate result is that the voltage-drop across some of the units is negligible, while the others are working at voltages much in excess of normal.

In reply to Mr. Bowden, it is not considered that high-frequency voltages (in the true sense of the term) have an appreciable effect on the test results, and the observed phenomena can adequately be explained in terms of ordinary power frequencies. The capacitance of the screened testing leads is about 50 $\mu\mu$F per ft., and the total shunting capacitance is not large enough to have any appreciable effect. Complete flashover of the insulator string probably takes place when, owing to the irregular potential distribution across the units and across parts of the same unit, the local voltage-gradient in the surrounding air becomes high enough to lead to ionization and breakdown.

The device mentioned by Mr. Whitehead can literally be described as a self-cleaning insulator. It was probably wise, however, to allow the patents to lapse.

In reply to Mr. Hill, the capacity of the testing transformer is 150 kVA. It is essential that a sufficiently large testing transformer should be used. In the present case the largest leakage surges commonly recorded have a value of only about 5 per cent of the full-load current of the transformer, and it is considered that the transformer capacity is quite adequate.

With regard to the voltage which should be employed for insulator testing, it is important that tests should be made at the working voltage, and it is true that measurements made at any other voltage may be very misleading. The normal working voltage to earth of the 132-kV grid lines is 76 kV, while the maximum working voltage is 85 kV, the voltage which was selected for test purposes.

The field in the neighbourhood of the insulators has not been investigated, and it seems probable that such an investigation would be more likely to lead to fruitful results in the case of pin-type insulators than in the case of cap-and-pin units.

In reply to Mr. Weaver, insulators have also been manufactured from ordinary glass, toughened glass, and Pyrex; but, in spite of its poor surface-resistance characteristics, porcelain still appears to be the most satisfactory material.

DISCUSSION ON
"THE HIGH-PRESSURE MERCURY-VAPOUR LAMP IN PUBLIC LIGHTING"*

WESTERN CENTRE, AT BRISTOL, 14TH DECEMBER, 1936

Mr. J. Fradsall Smith: The problem of improved highway lighting is not one for electrical engineers alone, and to achieve the best results the closest co-operation is necessary between illuminating engineers, highway engineers, and those who have occasion to use the roads for transport.

The nature of the surface of a road undoubtedly has a great effect on the efficiency of the lighting system installed, and it must be admitted that a lighting system which gives good results on clear dry nights can give very poor results when wet murky conditions prevail. Polished dark-coloured road surfaces appear to be the worst offenders, as they produce a road aspect which is divided sharply between completely black obscure patches and shiny patches which are almost dazzling in comparison. A number of roads recently have been covered with a coarse grey-green gravel, which appears little different under dark wet conditions from clear dry conditions.

There is, further, as most people who have driven cars this winter will agree, considerable scope for improvement of windscreen visibility. A well-illuminated road surface can be considerably nullified from a motorist's point of view by windscreens which do not permit a wide angle of vision and have a tendency continuously to become fogged and blurred.

Apparently the opinion is firmly held by some that local-authority economics may prevent the adoption of comprehensive and efficient highway lighting. Bearing in mind that the accident rate approaches 200 000 people a year (and with the increase of traffic there is every likelihood that if present road conditions continue the rate will rise), it must be apparent that if the loss due to these regrettable accidents could be assessed as money value their total annual cost would be extremely heavy. Many of these accidents must result from poor driving visibility, and the annual loss from this cause if capitalized would represent many millions of pounds of expenditure. The matter is therefore not one of local economics. It assumes the magnitude of a national problem, which must be treated nationally, in the same manner as ultimately the whole question of highways will be treated.

Modern highways, by reason of the nature and extent of their construction, are extremely costly, and it seems a pity that the benefit of such highways should be minimized for many hours of the day by the provision of ineffectual illuminating equipment. The development of lamps such as those described in the paper has provided an opportunity of illuminating roads more generously than has been possible for an equal amount of capital expenditure in the past.

Mr. Bernard Carlton Robinson: With reference to Fig. 11 and the question of the mains current, I note that the authors suggest that switchgear suitable for a filament lamp of the same light output as the h.p.m.v. lamp should be used. This means in practice that the rated current in the circuit should be multiplied by 3, to give the capacity of the switchgear. The mains-current curve in Fig. 11 does not appear to confirm that the capacity need be so high. Is there any other factor which influences the choice of switchgear?

Figs. 14 and 15 show typical arrangements of the choke and condenser for street lighting equipment. As discharge lighting is now being widely adopted in industrial premises, it is quite often necessary to mount this apparatus on walls and beams in ordinary buildings. Up to the present the makers do not appear to have placed on the market any chokes or condensers designed particularly for this purpose. Those designed for street-lighting use are not provided with screwed entry, and the loose leads from the choke are not ideal. Are the manufacturers bearing such points in mind, and may condensers and chokes of an industrial design be expected in the near future?

Finally, can the authors tell us whether recent research offers any hope of h.p.m.v. lamps being designed which do not require expensive accessories such as the choke and condenser for their normal operation?

Mr. S. Hartland: Though the mercury lamp and the sodium lamp both provide good visibility there appears to be a marked difference in the clarity of the light given by the two lamps, and this difference is not necessarily due to colour. I would liken the clarity provided by the mercury lamp to sunrise, and that provided by the sodium lamp to sunset, conditions.

Mr. W. A. H. Parker: No mention is made in the paper of the flickering effect which is inseparable from discharge lamps of all types, and I assume that no difficulty due to this effect has been experienced when using these lamps for street-lighting purposes. In the case of industrial applications we received some complaints, but they were overcome when we connected adjacent lamps to different phases of the supply.

Mr. Horace G. Weaver: I have had some experience of the use of the h.p.m.v. lamp in steelworks, where the temperature of the steel during rolling has to be estimated from its colour as judged by the eye. It was feared that h.p.m.v. lighting would affect the apparent colour and cause difficulty, and it was therefore introduced gradually, until the lighting consisted almost entirely of these lamps, but no difficulty was experienced in this respect. The mercury-vapour lamp has proved to be very successful when used for illuminating mills for cold-rolling bright steel strip, the surface of which has to be carefully watched for defects. The light from this type of source appears to show up defects more clearly than that from metal-filament lamps, but on the other hand it has led to difficulty in reading the markings on micrometers. The reason for this is rather obscure, as the readings can be obtained quite easily where metal-filament lamps are used but the foot-candle power of illumination is much lower.

---

* Paper by Messrs. G. H. Wilson, E. L. Damant, and J. M. Waldram (see vol. 79, pp. 241 and 501).

The starting characteristic of the h.p.m.v. lamp is a disadvantage for works lighting, as a momentary failure of the supply causes several minutes of total darkness, unless a number of metal-filament lamps are also used. Speaking generally, the new type of lighting has been welcomed by the workmen.

Mr. Harold Midgley: Whilst the paper primarily sets out to deal with the h.p.m.v. lamp in public lighting, it actually goes very much beyond this, as the comments on the installation refer equally well to any other form of lamp. In a similar way, whilst my remarks will be confined to the question of installation they are not limited to the use of mercury-vapour lamps.

With regard to spacing, the authors suggest not more than 300 ft. on both sides of a straight road (one lamp per 150-ft. run). Owing to the interference which may be caused by a large vehicle, I would strongly urge that this should certainly not be exceeded and that the shorter the distance permitted by financial considerations the better. I have found by experience that road brightness may be practically entirely lost to a driver following, say, a double-decked omnibus, owing to the latter shielding the light source, and the greater the spacing of the lights the longer does such interference last.

I should like to have the authors' opinion as to the relative merits of 125-watt h.p.m.v. lamps at 180-ft. spacing on both sides of a straight road (one lamp per 90-ft. run) as compared with 400-watt h.p.m.v. lamps at 250-ft. or even 300-ft. spacing on both sides of a straight road (one lamp per 125- to 150-ft. run). Although the watts per foot of the former are only about half those of the latter, will not there be a much smaller proportion of the road with black patches in the case of the smaller lamps more closely spaced? Further, the inconvenience due to the failure of a lamp will be less with the closer spacing.

It is interesting to compare the lighting of the Mersey Tunnel, where the consumption is 15 watts per foot run for a direct illumination of 1·5 to 2·0 foot-candles, with the use of 400-watt mercury-vapour lamps at 250-ft. spacing on both sides of a straight road (one lamp per 125-ft. run), and therefore requiring 3·2 watts per foot to give illumination by silhouette.

The authors do not make specific reference to the question of wet roads. In view of the fact that the visibility of a motorist is usually reduced in wet weather, no matter how efficient his windscreen wiper, it is essential that the road lighting should then be entirely satisfactory, but unfortunately water on a road surface totally alters the shape of the bright areas, considerably narrowing them. It is therefore essential that the public lighting should be designed to be adequate under wet-weather conditions, a point which very often appears to be overlooked.

Mr. D. R. Beckett: In view of the authors' advocacy of staggered lighting by means of lamps supported on posts at the side of the roads, and their remark that central suspension lighting is suitable for narrow roads only, I should like to have their opinion as to the maximum width of road (measured between kerbs) which can be illuminated satisfactorily by means of the central suspension system.

It appears to me that the light given by the 80-watt discharge lamp shown at the end of the authors' demonstration was of a somewhat more pleasing colour than that given by the 400-watt lamp shown at the beginning. I should therefore like to ask the actual percentages of red rays present in the light outputs of the two lamps.

Mr. L. F. A. Driscoll: Will the authors please state the reasons why the h.p.m.v. lamp has been developed in this country in preference to the sodium lamp, which has apparently met with very successful results in other countries?

Having regard to the disastrous effect of the upward bow of the arc softening the inner glass tube and causing a bulge due to the difference in pressure between the inner and outer envelopes when the lamp is tilted beyond 5° from the vertical, it would be interesting to know what these pressures are for both low-pressure and high-pressure mercury-vapour lamps.

It is understood that the 80-watt bayonet-cap lamp demonstrated by the authors requires a choke and condenser, and I should like to know whether they consider such units suitable for domestic application, and what the approximate cost per point would be. Possibly some colour correction would be necessary.

They state that the outer glass, which becomes the final radiator of heat, runs at a maximum temperature of about 350° C. in air. Does this statement apply to the smaller lamps such as the 80-watt bayonet-cap type demonstrated, as, if so, heat dissipation will be a serious problem.

Finally, it is regretted that the industrial application of the h.p.m.v. lamp is not dealt with in the paper, but perhaps the authors would be good enough to express their opinions on the use of this type of lamp in industrial situations such as factories with a considerable amount of turning machinery, and railway yards and sidings where coloured signalling is employed. In the former case stroboscopic effects may be experienced, and in railway work wrong colour aspects may be caused. Would men operating steel furnaces, forges, etc., meet with difficulty in judging the condition and temperature of metals owing to the radiant mixture of light and heat energy from the lamp source and the heated metal?

Mr. W. C. Bowler: I should like to ask the authors whether it is their considered opinion that eventually a type of lamp will be evolved to suit rural street-lighting conditions. It would also be interesting to know whether in view of the very high casualty list of the ordinary gasfilled lamps, in the long run it would be better to install lamps of the h.p.m.v. type. Bearing in mind the difficulty, particularly with steel-pole overhead lines, of dealing with the road-vibration troubles due to heavy traffic, would the running cost of h.p.m.v. lamps be lower, over a period of, say, 2 years, than that of existing gasfilled lamps?

Prof. D. Robertson: When the authors were demonstrating the 80-watt h.p.m.v, lamp, to those of us in this corner of the room it appeared as if seen through a curtain of vertical lines. Can the authors explain this phenomenon?

Mr. G. H. Wilson, Commander E. L. Damant, and **Mr. J. M. Waldram** (*in reply*): As several speakers have referred to the same subjects, it will be convenient to reply to the discussion by subjects, following the scheme of the paper, rather than to individual speakers.

Messrs. Hartland, Weaver, and Driscoll refer to the controversial question of the colour of the light; Mr. Weaver's remarks confirm our experience, that difficulties with the colour are for the most part due to unfamiliarity and prejudice, and disappear with use. It is probable that the differences in apparent " clarity " of the light from mercury and sodium lamps, mentioned by Mr. Hartland, are often due to causes other than the spectral distribution itself, such, for example, as differences in intensity distribution of light from fittings. There often seems to be some difference in appearance, but it has not so far been analysed, and it is probably partly psychological. The light from mercury lamps has been found suitable for fine work and the detection of cracks, as Mr. Weaver says: we are surprised that men found difficulty in reading micrometers by this type of light. Possibly the cause lay in the distribution of light or the location of the sources. In reply to Mr. Beckett, there is a slight difference of colour between the 125-watt lamp and the 400-watt. The percentage of red light (defined as that transmitted by a No. 25 Wratten red filter) is about 2 per cent for the 80-watt and 125-watt lamps as compared with 1 per cent for the larger lamps, but the effect on the colour of the light emitted by the lamps is not easy to see. The smaller lamps also emit rather more blue light. To avoid glare, in the demonstration the 400-watt lamp was not fully run up, and therefore appeared bluer than it would do under normal working conditions. Mercury lamps appear greenish at a distance in a slight haze and have consequently to be shaded near railways to avoid confusion with a " clear " signal, as Mr. Driscoll suggests. His question concerning the use of mercury lamps in steelworks has been answered by Mr. Weaver. The title of our paper, as well as limitation of space, did not allow us to deal with industrial applications of the lamps. The stroboscopic effect mentioned by Mr. Parker and Mr. Driscoll is of no importance in street lighting, where objects move at low angular speeds in the field of view. In industrial lighting the trouble is less than might be supposed, and Mr. Parker's remedy is usually satisfactory. The appearance of vertical lines noticed by Prof. Robertson is due to the shadows on the retina of small particles, cast by the long light source. If the lamp is turned on its side the lines appear to run horizontally.

In reply to Mr. Driscoll, the mercury lamp has been developed in this country in preference to the sodium lamp because it offers more possibilities of development. Although the sodium lamp is more efficient than the present mercury lamps, it is more costly, of lower brightness, and can only be made in small sizes: there is no practical prospect of easily improving its colour. The mercury lamp shows possibilities of development in both large and small sizes, it can be made to emit light at high brightness, and there is every possibility of being able greatly to improve its colour by the use of fluorescent materials—though the extent to which this is advantageous for street lighting is not yet certain. It also remains to be seen whether such correction may render small h.p.m.v. lamps suitable eventually for domestic lighting.

In reply to Mr. Bowler, we hope that the smaller sizes will be used for rural street lighting. The running pressure in the hard-glass lamps, for which Mr. Driscoll asks, is about 1 atmosphere, and in the quartz lamps about 10 atmospheres. The temperature of the outer glass bulb is, however, much lower with the 80- and 125-watt lamps, being of the same order as that of tungsten-filament lamps of comparable wattage. In reply to Mr. Bowler, the lamps have not been found to be sensitive to vibration and are stronger than the corresponding tungsten lamps. Costs should not be much affected by vibration except in extreme cases.

In reply to Mr. Robinson, at the present stage of development there is no prospect of making a discharge lamp which will not require some sort of series impedance. Although such auxiliaries involve an initial expenditure, their cost over 10 years amounts to less than 4 per cent of the energy and lamp-replacement cost with energy at 1d. a unit. Even if some device could be incorporated in the lamp it would be a replaceable item, and its cost would have to be very low to be cheaper in the long run than the independent choke and condenser. The design of chokes more suitable for industrial use is under consideration and they will be available in due course. It is desirable, as stated in the paper, to have switchgear of rather greater capacity than Fig. 11 would indicate, in order to deal with the momentary initial switching surge that may take place, which is not shown on Fig. 11. Careful design of the electrodes can keep this surge within reasonable limits.

Mr. Smith and Mr. Midgley both refer to the important subject of visibility in wet weather. As we stated in the paper, it is probably true that no system of lighting with punctiform sources can be as good when the road is wet as when it is dry, with many of the road surfaces at present in use. A system which is properly designed for dry conditions on the lines outlined in the paper will, however, be reasonably good when the road is wet. Some surfaces exist which when new give roughly the same results whether wet or dry, but the condition is not permanent. Some very rough roads, which do not flood in wet weather and therefore give good results when wet, are often so rough as to be almost impossible to light well when dry. Attention is now being directed to the problem by road engineers, and it is to be hoped that a surface will be found which makes a good compromise between the many requirements of reflection properties, wet and dry; non-skid properties; wear; maintenance; and cost. The system of lighting of which Mr. Midgley speaks, using low-power sources at short spacing, has one advantage, namely that in wet weather on a flooded road it provides a larger number of bright areas closer together, thus reducing the widths of dark areas between them. In dry weather, however, we doubt whether the installation which he describes would be as satisfactory as one with higher-power sources at longer spacing, and we should expect the cost of installation and maintenance to be greater than that of the type of installation described in the paper. Mr. Midgley does not mention mounting height: small lamps are usually mounted lower than 25 ft., and if this were done we should expect a definitely less satisfactory installation, and the centre relatively darker than in our "optimum" installation. If the mounting height were kept at 25 ft. this would not occur, but the whole level of brightness might be low. We welcome Mr. Midgley's confirmation of the undesirability of exceeding 150-ft. spacing. The question of shadows from large vehicles is one of the matters which influenced this recommendation; we have found little trouble at 150-ft. spacing but more trouble with much greater spacings. The trouble from this cause is accentuated in a meagre installation, for as the power of an installation is decreased the visibility is affected most in the shadows and dark regions. We are interested also in his reference to the lighting of the Mersey Tunnel, in which we have taken some measurements which confirm his conclusions. In reply to Mr. Beckett, we do not consider that central lighting is ever so satisfactory as side lighting on a given street. On carriageways not more than about 28 ft. in width, with light buildings or hoardings at the side and with adequate power, centrally-mounted units can give satisfactory results.

Finally, we welcome Mr. Smith's remarks, and look forward to the co-operation, which is already beginning, between lighting and road engineers and transport authorities; and to the time when the lighting of roads will be logically and efficiently controlled and scientifically designed.

DISCUSSION ON

"EQUIPMENT AND PERFORMANCE OF STEEL-TANK RECTIFIER TRACTION SUBSTATIONS OPERATING ON THE UNDERGROUND RAILWAYS OF THE LONDON PASSENGER TRANSPORT BOARD"*

NORTHERN IRELAND SUB-CENTRE, AT BELFAST, 19TH JANUARY, 1937

Mr. E. N. Cunliffe: The author shows that although backfires in steel-tank rectifiers are comparatively infrequent their effect on the 11 000-volt distribution system is very severe, much more so, in fact, than the effect of a dead short-circuit on the busbars. In consequence of this the rupturing capacity of the e.h.t. circuit breakers has had to be increased above the normal value. One would expect that such occurrences would have a disturbing effect on rotary plant in the vicinity, and that temporary loss of such plant might result. It would be interesting to learn the author's experiences of such conditions. The possibility of backfire in rectifiers is stated by him to be of little importance, but it appears to me that before this can be admitted the frequency of such happenings must be reduced to a figure comparable with that for e.h.t. faults on rotary-convertor equipment.

The author states that the London Passenger Transport Board's rectifiers have an overload capacity of 50 per cent for 1 hour and 200 per cent momentarily. A speaker at the discussion on this paper before another Centre spoke of a rectifier which had been successfully tested at overloads of 100 per cent for 2 hours, 150 per cent for ½ hour, and 250 per cent for 5 minutes. Further, I understand that a rectifier on the Manchester South Junction and Altrincham Railway was subjected to a very severe overload test under service conditions over a period of several months, during which the loads applied exceeded five times full load on many occasions; the test resulted in only a few disconnections of the rectifier, and no damage. It would therefore be interesting if the author could state what is the true factor of safety upon which his overload ratings are based, in view of his experience of the behaviour of the rectifiers under service conditions. In the light of this experience would he expect future rectifiers of similar dimensions to be more liberally rated?

Mr. F. Johnston: I gather that any future extensions to the Board's traction substations will be equipped with rectifiers, and that the author does not propose to add any more rotary convertors. I should like to know whether he would contemplate a system consisting entirely of rectifiers, seeing that this would mean that the power factor of the system could not be more than 94 per cent.

On page 125 he shows that the kWh supplied from the rectifier plant are only about 10 per cent of the total, and states that the capacity of rectifier plant supplied from Lots Road is 30 000 kW, the capacity of rotary plant being 125 200 kW. It appears from these figures that the percentage standby in the case of rectifier plant, which is over 19 per cent of the installed plant, is much larger than in the case of rotary plant, and I should appreciate his remarks on this point.

I note that he uses two types of seal—mercury and porcelain. I take it that when a porcelain seal is broken there is considerable trouble in replacing it. Does the author favour porcelain seals in preference to mercury seals?

I should like to know what his experience has been with d.c. ignition as compared with a.c. ignition, as I note that both types are used on his system.

Mr. J. E. Jones: There is one glass-bulb rectifier installation in Belfast, and several years ago I was very interested in its apparent instability at light load when running in parallel with a rotary convertor at a distant substation. Its capacity was about 70 kW, but it would not settle down on load until it was taking at least 8 or 9 kW. It would interchange load with the distant rotary, with consequent flickering of the lights, until the transformer taps were increased and the critical load was exceeded. Has the author any experience of such apparent instability at light load with steel-tank rectifiers running in parallel with rotary convertors?

---

* Paper by Mr. A. L. Lunn (see vol. 78, p. 123).

Mr. Joseph McCandless: The author stresses the importance of reliability in connection with the design of substations, and yet uses cubicle-type switchgear instead of modern armourclad switchgear. I should like to know why he does this.

I notice also that he places the oil switch on the top floor of the substation, the h.t. busbars being immediately underneath, with cable connections from one to the other. It would appear that if the switch above should fail and an oil fire take place, burning oil running down the cable on to the h.t. busbars would cause a busbar fault. Has the switchgear used any particular merits which would prevent this happening in the case of a switch failure and, if so, what are these merits?

The author states that if a rectifier backfires the switchgear is submitted to severe strain. Does he mean that if switchgear is designed for a certain rupturing capacity and installed on a system where this capacity would not be exceeded, in the event of a rectifier backfire the switch might be damaged? If so, in what way should the rupturing capacity be determined so as to ensure safe operation of switchgear under these conditions?

Mr. R. P. Watson: The London Passenger Transport Board seem to have been remarkably successful in obtaining sites for substations of such ample proportions as those shown both in the paper and upon the screen. I am particularly struck with the layout of the plant in these stations and with the provisions which have been made for cables.

On page 126 it is stated that, by sinking the rectifier partly through the floor, connection to the cathode is facilitated and general accessibility of the plant as a whole improved. On page 134, however, the author goes on to say that very considerable economies may be effected by locating the plant on an upper floor of the substation building. I should have thought the contrary to be the case, but apart from the question of economy is the practice of installing a complete substation on an upper floor desirable?

What precautions are taken in these unattended substations against the risk of fire, especially fire due to burning oil such as might occur in the event of high-voltage switchgear explosions? I cannot see that the use of copper strip for connections, instead of cables, as mentioned on page 129, minimizes to any great extent fire risk, as there would appear to be already a considerable amount of cable installed.

The present-day paper-insulated and lead-covered cable is one of the most reliable components in any electrical installation. I imagine that in substations of this type, to which cleaners and such like people have access, the risk of fire due to the use of cable is outweighed by the risk of shock. Have the Board experienced any accidents?

In Table 4 the figure for the percentage of failures due to control gear appears to be very high. Seeing that reliability is of primary importance does the author not consider manual operation, though possibly less economic, more advisable for maintaining continuity of supply, in any case until such time as control gear proves to be more satisfactory than it would appear to be to-day from the figures given in Tables 4 and 5? He states on page 127 that the equipment may be controlled locally. Has this method of control been resorted to for a considerable period in any station, and, if so, by what amount has the percentage of total failures been reduced?

With reference to the cooling systems of rectifiers, I understand that a satisfactory method of air cooling is now obtainable; this would appear to have obvious advantages over the water-cooling method. Has the author any information regarding the efficiency and reliability of air-cooled steel-tank rectifiers? Their adoption might reduce appreciably those percentages in Tables 4 and 5 attributed to the water system.

He states on page 135 that the distortion of voltage and current waves is of little practical importance, since the rectifier load is only about 10 per cent of the peak load on Lots Road station; but since the paper was written this figure has risen to 17 per cent. At what figure does the author consider that distortion of waveform would constitute a serious factor?

Mr. W. A. Frazer: It is very interesting to note the author's apparent preference for cubicle-type h.t. switchgear; this preference would at first sight appear to be justified by the recent failures of armourclad switchgear in this country. It appears to me, however, that the relative freedom from failures of cubicle-type switchgear has been due, not to superior design, but to the fact that armourclad switchgear has been installed in most places where the switchgear would be called upon to operate under very onerous conditions. In America, where cubicle-type switchgear has been installed in large power stations, a considerable number of failures has occurred, and in some instances these failures have caused the destruction of a complete switchboard instead of being limited to one or two switches as has happened in this country where armourclad switchgear has been involved.

Mr. A. L. Lunn (*in reply*): In reply to Mr. Cunliffe, I am unable to agree that, in general, the backfiring of a rectifier can be classed in the same category as a fault on the a.c. side of a rotary convertor. Troubles of the latter description are, almost without exception, due to some weakness in the affected unit, and are liable to involve the carrying out of repairs which may be of considerable magnitude and correspondingly high cost. On the other hand, backfiring is brought about in the majority of instances as a result of abnormal conditions of operation; under such circumstances the rectifier can safely be reconnected to the supply immediately the pumps have restored the vacuum to normal, usually a matter of seconds only. Hence, in my opinion, a backfire becomes comparable with a rotary-convertor a.c. fault only in such rare instances as those where the underlying cause of the rectifier failure is actually that of a fault in the internal parts of the unit itself, or where some part of the equipment sustains damage as a direct result of a backfire occurring under abnormal conditions of operation. The frequency of occurrence of rectifier failures of this nature is, within my experience, probably less, and certainly no greater, at the present time than that of faults on the a.c. side of rotary convertors.

As regards the effect of a heavy backfire on synchronous plant connected to the system, this has been found to be negligible—the resultant momentary voltage fluctuation that is usually set up being of insufficient magnitude to interfere with the proper running of the rotary convertors.

The overload trials to which Mr. Cunliffe refers were, of course, exceptionally severe, and constituted a very searching test of the reliability of the rectifier under abnormal conditions of operation. In my opinion, however, it is not advisable to rely upon the capacity of rectifier plant to deal with overloads of such magnitudes as those mentioned, although it is probable that, in the case of systems on which unbroken continuity of supply is less urgent than on the Underground Railways, more liberal ratings than those indicated in the paper would be permissible.

Mr. Johnson is correct in his deduction, from the published figures, that the proportion of standby plant is considerably greater in the rectifier than in the rotary-convertor substations. It is pointed out, however, that in the majority of cases the former installations are located in outlying districts, where rapid development is now in progress; a considerable increase is expected in the volume of traffic to be dealt with on all sections of line serving these districts, and when this materializes much of the present standby rectifier plant will be brought into continuous service.

The same speaker also inquires as to whether rotary convertors will ultimately be entirely displaced from the Underground substations by rectifier plant. It is highly improbable that such a change-over would be contemplated, not only on account of the accompanying unavoidable deterioration in the system power-factor, but also since trouble might be experienced as a result of excessive distortion of the system voltage-wave, which, as stated in the paper, would be likely to entail derating of the generators.

This question of voltage-wave distortion is referred to by Mr. Watson, who inquires as to the proportion of rectifier load to total load on the generators which would be regarded as being a safe maximum. I regret that in the absence of complete test data I am as yet unable to give a definite reply to this question, but it is certain that a very considerable increase in the present rectifier load on the system is still permissible.

Dealing with Mr. Johnson's further inquiries regarding the replacement of anode seals, it is assumed that reference is made to the vitreous enamel type of seal employed on the Western Extension rectifiers. Up to the present time it has not been necessary to effect any such replacement, but should a vitreous enamel seal become faulty it would be necessary to remove the anode stem, complete with seal, and return it to the manufacturers for rectification of the trouble. The work of replacing the anode assembly in the tank and remaking the vacuum joints between the anode seal and the rectifier top plate is a relatively simple matter, as may be seen by reference to Fig. 12 of the paper, and to Section 3 of my reply to the London and other discussions (see vol. 78, page 674), where a description is given of the construction of the joint.

In the same Section of that reply also my opinions regarding the relative advantages and disadvantages of d.c. and a.c. ignition systems respectively have been fully detailed, the additional experience I have gained since the publication of the paper having in no way modified my views.

Mr. Jones comments upon a case of instability experienced in operating a glass-bulb rectifier in parallel with a rotary convertor located in a distant substation. Up to the present time no similar case has occurred on the Underground system, but it would have been interesting had details been given of the steps taken to overcome the difficulty referred to.

I agree with Messrs. McCandless and Frazer that there is much to be said in favour of metalclad switchgear. On the other hand, as I have already pointed out during previous discussions, the accessibility of cubicle-type e.h.t. gear is considered to be sufficient to justify its use in Underground substations.

Mr. McCandless appears to be labouring under a misapprehension regarding the arrangement of the e.h.t. switchgear illustrated in Fig. 6. The construction of the cubicles is such that it is impossible for oil to pass from the upper to the lower sections, the connections from the oil-switch cubicles to the busbars being effected by means of strip copper passing through bush-type floor insulators from one chamber to the other. These insulators are carefully sealed off with special compound to prevent the passage of oil.

Regarding the determination of the minimum rupturing-capacity oil switch that can safely be used on a rectifier circuit, in view of the lack of precise information on the subject I am unable to give any indication as to the theoretical basis on which such a calculation can be made. As stated in the paper, subsequent to the trouble experienced at Hendon substation it was decided to provide all rectifier circuits with oil switches of 40 % greater rupturing capacity than those which would be provided for rotary convertors situated at the same points. This practice will be continued until more definite knowledge as to the actual conditions to be met is available.

The severe fault conditions under which rectifier oil circuit-breakers are called upon to operate are apparently the result of the heavy d.c. magnetization of the transformer core, which occurs at the moment of backfire.

I note that Mr. Watson does not agree with the location of a substation on an upper floor of a building, either from the point of view of economy or from that of good practice. In regard to the economics of the situation, I would point out that, by reason of the high capital cost of sites in the London area, considerable revenue becomes available if the ground floor of the substation building is available for letting purposes; it may be remarked in passing that the trial of this method of construction that has been made in the case of Leicester Square substation has proved to be very satisfactory, the whole of the ground floor having been let off as showrooms.

As regards the second objection, Mr. Watson does not attempt to make out any case against the installation of a complete substation on an upper floor. In my opinion, although this arrangement is a departure from normal it cannot be regarded as bad practice purely on that account, and I am satisfied that it is possible to find more arguments for than against the scheme.

In reference to the suggestion made by the same speaker as to the advisability of substituting manual for remote-control operation of the substations in order to eliminate failures due to the faults in the control gear, I would point out that although, as shown in Tables 4 and 5, approximately 50 % of the breakdowns experienced during the 12-monthly period considered were due to remote-control gear troubles, the total number of breakdowns amounted to 48 only, distributed amongst 32 rectifiers. Failures due to control gear, therefore, were responsible for 24 shut-downs, which works out at an average of 0·75 per rectifier per annum. This figure cannot be regarded as being sufficiently serious to warrant the additional expense of keeping attendants at each substation.

The main point which it was desired to emphasize in the paper was that, of the total number of failures from any cause during the period covered by the analysis, the proportion due to control-gear faults was excessively high, and could probably be reduced by increased care in design.

I regret that I have no records, other than those already published, indicating the degree of increased reliability that can be obtained by the adoption of manual operation in preference to remote operation of the substations.

In regard to the use made of copper strip for the connections between the d.c. busbars and switchgear, it is believed, as stated in the paper, that some reduction of fire risk is obtained thereby. There are, however, further advantages to be gained, particularly in the way of obtaining a neat layout. Dealing with the suggestion that the advantage of reduced fire risk is outweighed by the risk of shock to cleaners and similar untrained people, it is pointed out that such persons are permitted to enter unattended substations only when accompanied by one who is an authorized person within the meaning of the Home Office Regulations. The responsibility for taking all necessary precautions against accident rests upon this authorized person, who may be a tester or a substation official, and I am able to state that this system has been found to work satisfactorily, there having been no accident of the nature referred to by Mr. Watson.

In connection with the reference made to the new air-cooled steel-bottle rectifier now obtainable, I am able to state that the 750-kW equipment of this type which has been in operation on the Board's trolleybus system for approximately 14 months has given the utmost satisfaction. I am informed that its efficiency characteristic is very similar to that indicated in Table 2 of the paper, and those responsible for the running of the plant also speak very highly of its reliability. As a result of the success of this trial, other similar units have been purchased by the Board and will be brought into service in trolleybus substations in the near future.

PROCEEDINGS OF THE INSTITUTION

903RD ORDINARY MEETING, 5TH NOVEMBER, 1936

Mr. H. T. Young, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 22nd October, 1936, were taken as read and were confirmed and signed.

Messrs. C. L. Lipman and S. A. Stigant were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, it was reported that the members whose names appeared on the lists (see vol. 79, page 688) had been duly elected and transferred.

The President announced that, during the month of October, 47 donations and subscriptions to the Benevolent Fund had been received, amounting to £81. A vote of thanks was accorded to the donors.

A paper by Messrs. T. E. Allibone, D.Sc., Ph.D., Associate Member, D. B. McKenzie, B.Sc., Graduate, and F. R. Perry, M.Sc.Tech., Associate Member, entitled "The Effects of Impulse Voltages on Transformer Windings" (see page 117), was read and discussed. The paper was illustrated by a cinematograph film and accompanied by a demonstration of apparatus.

A vote of thanks to the authors, moved by the President, was carried with acclamation.

904TH ORDINARY MEETING, 19TH NOVEMBER, 1936

Mr. H. T. Young, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 5th November, 1936, were taken as read and were confirmed and signed.

A paper by Mr. L. H. Harris, M.Sc., Member, and Messrs. E. H. Jolley and F. O. Morrell, B.Sc., Associate Members, entitled "Recent Developments in Telegraph Transmission and their Application to the British Telegraph Services" (see page 237), was read and discussed. The paper was accompanied by a demonstration of apparatus.

A vote of thanks to the authors, moved by the President, was carried with acclamation.

905TH ORDINARY MEETING, 3RD DECEMBER, 1936

Mr. H. T. Young, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 19th November, 1936, were taken as read and were confirmed and signed.

The President announced that, during the month of November, 38 donations and subscriptions to the Benevolent Fund had been received, amounting to £16. A vote of thanks was accorded to the donors.

A paper by Dr. P. Dunsheath, O.B.E., M.A., Member, entitled "Continuous Extrusion of Lead Cable-Sheaths" (see page 353), was read and discussed.

A vote of thanks to the author, moved by the President, was carried with acclamation.

906TH ORDINARY MEETING, 17TH DECEMBER, 1936

Mr. H. T. Young, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 3rd December, 1936, were taken as read and were confirmed and signed.

The President reported the receipt by him of a Memorandum from the Keeper of H.M. Privy Purse, stating that His Majesty The King was pleased to intimate to those Societies and Institutions which were recently granted Patronage by King Edward VIII that they may continue to show the Sovereign as their Patron during the present Reign, unless otherwise notified.

The following papers were read and discussed: "The Micro-Gap Switch" (see page 457), by Prof. W. M. Thornton, O.B.E., D.Sc., D.Eng. (Past-President); and "Restriking Voltage, and its Import in Circuit-Breaker Operation" (see page 460), by Messrs. H. Trencham, Member, and K. J. R. Wilkinson, B.Sc., Associate Member.

A vote of thanks to the authors, moved by the President, was carried with acclamation.

INSTITUTION NOTES

INDEX TO JOURNAL

Any member who proposes to bind the current volume of the *Journal* and would like to have an extra copy of the Index for filing apart from the bound volume of the *Journal* can obtain an additional copy on application to the Secretary.

MEMBERS FROM OVERSEAS

The Secretary will be obliged if members coming home from overseas will inform him of their addresses in this country, even if they do not desire a change of address recorded in The Institution register.

The object of this request is to enable the Secretary to advise such members of the various meetings, etc., of The Institution and its Local Centres, and, when occasion arises, to put them into touch with other members.

COMMUNICATIONS FROM OVERSEAS MEMBERS

Overseas members are especially invited to submit, for publication in the *Journal*, written communications on papers read before The Institution or published in the *Journal* without being read. The contributor's country of residence will be indicated in the *Journal*. In this connection a number of advance copies of all papers read before The Institution are sent to each Local Hon. Secretary abroad to enable him to supply copies to members likely to be in a position to submit communications.

INTERNATIONAL ENGINEERING CONGRESS, GLASGOW, 1938

The attention of members is drawn to the International Engineering Congress which will be held in Glasgow in June, 1938 (provisional date, 21st to 24th June), on the occasion of the Empire Exhibition which will be in progress in Glasgow at that time.

A General Committee of the Congress, representative of the various engineering Institutions, has been formed under the presidency of Lord Weir, and the details of the programme are now being prepared by executive committees sitting in Glasgow and London. The Congress will include technical sessions, visits to the Empire Exhibition and to works, and social functions. Full information will be circulated to members at a later date.

The Committee of the I.E.E. Scottish Centre propose to hold their local Summer Meeting for 1938 at the Exhibition, concurrently with the proceedings of the Congress.

PREMIUMS

The Council have made the following awards of Premiums for papers during the session 1936–37:—

The Institution Premium (*value* £25).

E. A. Speight, Ph.D., and O. W. Gill	"The Post Office Speaking Clock."

The Ayrton Premium (*value* £10).

Douglas Robertson, M.A., B.M., M.R.C.P.	"The Examination and Recording of the Human Electrocardiogram by means of the Cathode-Ray Oscillograph."

The Fahie Premium (*value* £10).

Col. A. S. Angwin, D.S.O., M.C., and R. A. Mack	"Modern Systems of Multi-Channel Telephony on Cables."

The Kelvin Premium (*value* £10).

T. E. Allibone, D.Sc., Ph.D., D. B. McKenzie, B.Sc., and F. R. Perry, M.Sc. Tech.	"The Effects of Impulse Voltages on Transformer Windings."

The Paris Exhibition (1881) *Premium* (*value* £10).

J. A. Sumner	"Modern Factors affecting Electricity Costs and Charges."

A Premium (*value* £10).

P. Dunsheath, O.B.E., M.A., D.Sc.	"Continuous Extrusion of Lead Cable-Sheaths."

A Premium (*value* £10).

L. H. Harris, M.Sc., E. H. Jolley, and F. O. Morrell, B.Sc.	"Recent Developments in Telegraph Transmission, and their Application to the British Telegraph Services."

A Premium (*value* £10).

H. Trencham and K. J. R. Wilkinson, B.Sc.	"Restriking Voltage, and its Import in Circuit-Breaker Operation."

A Premium (*value* £5).

W. R. Debenham, B.Sc.	"The Performance of Coil Ignition Systems, with particular reference to Double Contact-Breakers and the Effects of Variation of the Period of Open Circuit."

A Premium (*value* £5).

W. Jackson, D.Sc., D.Phil.	"A Record of Recent Progress towards the Correlation of the Chemical Composition, the Physical Constitution, and the Electrical Properties, of Solid Dielectric Materials."

A Premium (*value* £5).

H. A. Thomas, M.Sc.	"The Electrical Stability of Condensers."

An Overseas Premium (*value* £15).

A. L. Green, M.Sc., Ph.D., and G. Builder, Ph.D.	"Control of Wireless Signal Variations."
A. L. Green, M.Sc., Ph.D., and O. O. Pulley, B.E., Ph.D.	"Control of Phase-Fading in Long-Distance Radio Communication."

WIRELESS SECTION PREMIUMS

The Duddell Premium (*value* £20).

M. Benjamin, B.Sc., Ph.D., C. W. Cosgrove, B.Sc., and G. W. Warren, B.Sc.	"Modern Receiving Valves: Design and Manufacture."

A Premium (*value* £10).

Commander F. G. Loring, O.B.E., R.N., W. L. McPherson, B.Sc.(Eng.), and W. H. McAllister	"A Survey of Marine Radio Progress, with special reference to R.M.S. 'Queen Mary.'"

A Premium (*value* £10).

T. L. Eckersley, B.A., B.Sc.	"Ultra-Short-Wave Refraction and Diffraction."

METER AND INSTRUMENT SECTION PREMIUMS

A Premium (*value* £10).

W. F. Randall, B.Sc.	"Nickel-Iron Alloys of High Permeability, with special reference to Mumetal."

A Premium (*value* £10).

E. Hughes, Ph.D., D.Sc.	"Magnetic Characteristics of Nickel-Iron Alloys with Alternating Magnetizing Forces."

A Premium (*value* £5).

C. Dannatt, D.Sc.	"The Variation of the Magnetic Properties of Ferro-Magnetic Laminae with Frequency."

A Premium (*value* £5).

Prof. J. T. MacGregor-Morris and V. A. Hughes, M.Sc.(Eng.)	"Experimental Verification of the Theory of the Cathode-Ray Oscillograph; and the Influence of Screen Potential."

TRANSMISSION SECTION PREMIUMS

The Sebastian de Ferranti Premium (*value* £20).

H. G. Taylor, M.Sc. (Eng.)	"The Use of Protective Multiple Earthing and Earth-Leakage Circuit Breakers in Rural Areas." (E.R.A. Report.)

A Premium (*value* £10).

J. Eccles, B.Sc.	"The Efficient Rating and Disposition of Supply Apparatus on High-Voltage Urban Systems."

The awards for papers read before the Students' Sections will be published later.

COUNCIL'S NOMINATIONS FOR ELECTION TO THE COUNCIL

The following have been nominated by the Council for the vacancies which will occur in the offices of President, Vice-President, Honorary Treasurer, and Ordinary Members of Council, on the 30th September, 1937:—

President. (*One Vacancy.*)

Sir George Lee, O.B.E., M.C.

Vice-Presidents. (*Two Vacancies.*)

Sir Noel Ashbridge, B.Sc.(Eng.).
J. R. Beard, M.Sc.

Honorary Treasurer. (*One Vacancy.*)

W. McClelland, C.B., O.B.E.

Ordinary Members of Council.

Members. (*Four Vacancies.*)

Col. A. S. Angwin, D.S.O., M.C.
H. J. Cash.
P. L. Rivière.
C. D. Taite.

Associate Members. (*Two Vacancies.*)

T. E. Allibone, D.Sc., Ph.D.
G. A. Whipple, M.A.

Companion. (*One Vacancy.*)

E. Leete.

PROCEEDINGS OF THE METER AND INSTRUMENT SECTION

63rd Meeting of the Meter and Instrument Section, 6th November, 1936

Mr. O. Howarth, the retiring Chairman of the Section, took the chair at 7 p.m.

The minutes of the meeting held on the 1st May, 1936, were taken as read and were confirmed and signed.

Mr. Howarth announced the Council's award of Premiums (see vol. 78, page 726) for papers read before the Section during the session 1935–36. He then vacated the chair, which was taken by Mr. G. F. Shotter, the new Chairman of the Section.

A vote of thanks to Mr. Howarth for his services as Chairman during the session 1935–36, proposed by Mr. H. Cobden Turner and seconded by Mr. F. E. J. Ockenden, was carried with acclamation.

Mr. Shotter then delivered his Inaugural Address (see page 10).

A vote of thanks to Mr. Shotter for his Address, proposed by Mr. E. W. Hill and seconded by Prof. J. T. MacGregor-Morris, was carried with acclamation.

64th Meeting of the Meter and Instrument Section, 4th December, 1936

Mr. G. F. Shotter, Chairman of the Section, took the chair at 7 p.m.

The minutes of the meeting held on the 6th November, 1936, were taken as read and were confirmed and signed.

A paper by Messrs. E. A. Speight, Ph.D., and O. W. Gill, entitled "The Post Office Speaking Clock" (see page 493), was read and discussed. Demonstrations were given in connection with the paper.

A vote of thanks to the authors, moved by the Chairman, was carried with acclamation.

65TH MEETING OF THE METER AND INSTRUMENT SECTION,

8TH JANUARY, 1937

Mr. G. F. Shotter, Chairman of the Section, took the chair at 7 p.m.

The minutes of the meeting held on the 4th December, 1936, were taken as read and were confirmed and signed.

A paper by Mr. W. F. Randall, B.Sc., entitled "Nickel-Iron Alloys of High Permeability, with special reference to Mumetal" (see page 647), was read and discussed. At the conclusion of the discussion, demonstrations were given by Mr. G. A. V. Sowter.

A vote of thanks to the author, moved by the Chairman, was carried with acclamation.

PROCEEDINGS OF THE TRANSMISSION SECTION

15TH MEETING OF THE TRANSMISSION SECTION,

11TH NOVEMBER, 1936

Mr. W. Fennell, the retiring Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting held on the 13th May, 1936, were taken as read and were confirmed and signed.

Mr. Fennell announced the Council's award of Premiums (see vol. 78, page 727) for papers read before the Section during the session 1935–36. He then vacated the chair, which was taken by the new Chairman, Dr. P. Dunsheath, O.B.E., M.A.

A vote of thanks to Mr. Fennell for his services as Chairman during the session 1935–36, proposed by Mr. S. R. Siviour and seconded by Mr. H. W. Grimmitt, was carried with acclamation.

Dr. Dunsheath then delivered his Inaugural Address (see page 21).

A vote of thanks to the Chairman for his Address, proposed by Mr. Fennell and seconded by Major W. M. N. Morecombe, was carried with acclamation.

Mr. R. Borlase Matthews then exhibited a selection of cinematograph films and photographs taken by members during the visits of the Section to Mid-Cheshire and to France.

16TH MEETING OF THE TRANSMISSION SECTION,

9TH DECEMBER, 1936

Dr. P. Dunsheath, O.B.E., M.A., Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting held on the 11th November, 1936, were taken as read and were confirmed and signed.

A paper by Mr. W. Holttum, B.Eng., Member, entitled "The Jointing and Terminating of High-Voltage Cables" (see page 517), was read and discussed.

A vote of thanks to the author, moved by the Chairman, was carried with acclamation.

ELECTIONS AND TRANSFERS

At the Annual General Meeting of The Institution held on the 6th May, 1937, the following elections and transfers were effected:—

Elections

Members

Dadge, Benjamin Nelson.
Rüdenberg, Reinhold, Dr. Ing.

Associate Members

Barton, George Donald.
Coates, Thomas, M.Eng.
Hansell, John Bentley, B.Sc.
Harrison, George Bernard W.
Honey, Philip Cecil.
Inder, Alfred James, B.Sc.
Keeley, Percy William.
Lyddall, Audley George.
McAllister, William Hugh.
O'Mongáin, Breandan, B.Sc.(Eng.).
RangaRao, Konasur Narayana, B.E.
Reed, Edwin Charles.
Spruce, Allan Mason.
Stott, Bertram Edward.
Wainscot, Francis Stanley, Flight Lieut., R.A.F. (Ret.).
Wilcockson, Harold Ernest.

Associates

Adam, Harold.
Booth, Joseph Couldwell.
Crawford, James.
Cutler, William Ronald.
Field, Joseph McNeight C.
Hulley, John Muirhead.
Lees, David William.
Margrave, John Thomas D.
Mitchell, Ewart Pearce.
Newton, William Henry.
Stewart, Edward Oswin.
Wingett, Albert William.

Graduates

Alcock, Arthur.
Austwick, Harwood Richard J.
Berry, Robert.
Bonfa, Norman, B.Sc.(Eng.).
Cuffe, Robert Cormac, B.E.
Dannenberg, Kurt, Dipl. Ing.
Davis, Allan.
England, Arthur Keith, B.Sc.
Gage, Edgar James.
Grensted, John, B.Sc. (Eng.).
Higgins, Thomas Anthony.
Horner, Harold.
Kaplanski, Wlodzimierz, Dipl.Ing.
Kerwin, William Edward.
Lejeune, Sydney Maurice.
Mallet, Roger.
Mistry, Bomanshaw Merwanji.
Newton, Stuart William, B.Sc.
Ramarao, Jata Venkata.
Roxburgh, Albert.
Rundell, Charles.
Searle, George, M.Sc.
Shannon, John, B.Sc.
Southby, Arthur Cyril.
Stratton, Ronald Edward, B.Sc.
Tahseen, Sheikh Mohamed.
Thomson, Alfred Samuel.
Yeo, Thomas Chaplin, M.A.

Students

Abbott, Rolfe Merton F.
Allan, Arthur Quinton.
Allen, Ralph Westbrook.
Allison, Alexander Bernard.
Anderson, James.
Atkinson, Arthur Ralph.
Aust, John.
Baker, Stephen George.
Beardsworth, Russell.
Beecham, Ronald Arthur.
Bell, James Keith.
Bellairs, Leonard George.
Bentley, Hugh Roland B.
Bertram, Thomas Hindess.
Best, Denis.
Boden, George Harry.
Bonson, Leslie Edwin.
Borrill, Leonard Thomas.
Botterill, Arthur Ronald.
Bowyer, Ronald.
Briggs, Harry Kenneth.

Students—continued.

Broadbent, Harold.
Buckley, Sam.
Bull, Raymond.
Burt, Harry Kyle P.
Chadwick, Thomas Herbert.
Clay, George Robert.
Clunie, Matthew.
Cooper, Sydney John.
Cotterell, Joseph.
Cranmer, John Michael.
Dark, Cyril Montague.
de'Mello, John Stephen.
Dixon, John George.
Donald, William Horace.
Donoghue, Vincent.
Doughty, Robert Henry.
Dykes, James Oswald.
Eden, John Frederick G.
Emery, William John G.
Everett, George James.
Facey, John Morris C.
Fawssett, Phyllis Armorel M. (Miss).
Field, George.
Finnis, Ronald Tavenor.
Fonseka, Wijesinghege Wenceslaus.
Forster, John Arnold.
Frost, Ernest Mark.
Graham, Frank.
Gregory, William Edmund.
Habicht, Ronald Charles.
Hadland, Peter.
Hales, Arthur Collingwood.
Harrison, David Wallis.
Harrison, Denis Goodwin.
Hartill, Philip.
Herd, John Albert.
Hill, Ernest.
Horner, Norman.
Hughes, Raymond Ernest.
Hunt, Alan William J.
Hunt, Peter.
Hyne, Graham Everett.
Imison, Kenneth Halton.
Jackson, Alexander Frederick.
Jeffery, Derek William.
Jennings, Frederick Kenneth.
Jewell, David Seymour, B.Sc.(Eng.).
Kaul, Permashwar Nath.
Kerawalla, Rusi Dhanjishaw.
Knight, Harold Phillips.
Leitch, John Forsythe B.
Lightbourne, Arthur.
Love, William Andrew H.
Maaraba, Abd El-Hamid.
McDougall, Kenneth Gordon.
McEwan, Ronald Bruce.
Mahil, Jagat Singh.
Mansfield, Ifor Harland.
Margolis, Leon Phillip.
Marshall, Charles John.
Martin, James McMaster.
Merry, Robert George.
Millar, Archibald Linton J.
Miller, Jack.
Moloney, John Lawrence H.
Moore, Alfred Henry H.
Mukerjee, Amitav.
Nageswaran, Kuppuswami, B.A.
Nangia, Lachhman Narain.
Natesan, Surianallur Venkatasubramania, B.Sc.
Newnham, Leonard Albert.
Nichols, Harold Wilfred.
Nicholson, Edward.
Nunn, James Edward.
Ord, John Ainsley.
Page, Robert Edward.
Panemanglor, Anand Krishnarao.
Parks, Fred.
Pick, Francis.
Pote, Wilfrid Eric.
Ramanujam, R.
Rangaswamy, Krishnaswamy, B.Sc.
Reddcliff, Ernest George.
Rees, William Roderick.
Reichert, Charles, Jun.
Ryness, Joseph Woolfe.
Sarwate, Manohar Balaji, B.Sc.
Scott, Bruce Glazier.
Sellar, James Alexander.
Sethna, Bomi Peroshaw.
Shepherd, Sydney Allan.
Sigee, Eric.
Smith, Ronald Edward.
Smyth, Ralph Patterson.
Stevens, Paul.
Subrahmanyam, P.Ch.
Swan, John Henry.
Swanston, Harold.
Swift, Brian Mastin.
Tattersall, Harry.
Terry, George Albert.
Thomas, Ambrose Bramwell.
Thompson, Russell Clare.
Thornton, Richard Morris.
Tibbs, Christopher Evan.
Tsu, Foonghsiang.
Tunstall, Douglas.
Tyson, George Marshall.
Vaughan, Harold James.
Vithal, S.
Walley, Arthur Howarth.

Students—continued.

Wallwork, Kenneth.
Ward, George.
Weinstock, Jack.
Welbourn, Donald Burkewood.
Welch, Brian Herbert.
Widdowson, Albert.
Wilding, Albert John F.
Woods, Cecil Herbert.
Woolfson, Mark.
Wright, Charles Hulse.
Young, David Grange.

Transfers

Associate Member to Member

Allcock, William Rayner.
Craven, James Gaunt.
Mathieu, Camille Nicolas.
Mellor, Leonard.
North, Benjamin, B.Eng.
Robertson, Alexander Paterson.
Saunders, James Reginald W., B.Sc.
Strong, Charles Eric, B.A.I.
Taylor, Thomas Alfred.

Associate to Member

Ferranti, Vincent Ziani de.

Associate to Associate Member

Fuge, William Valentine G., Major.
Laverick, Percy William.
Parker, William Clifford.

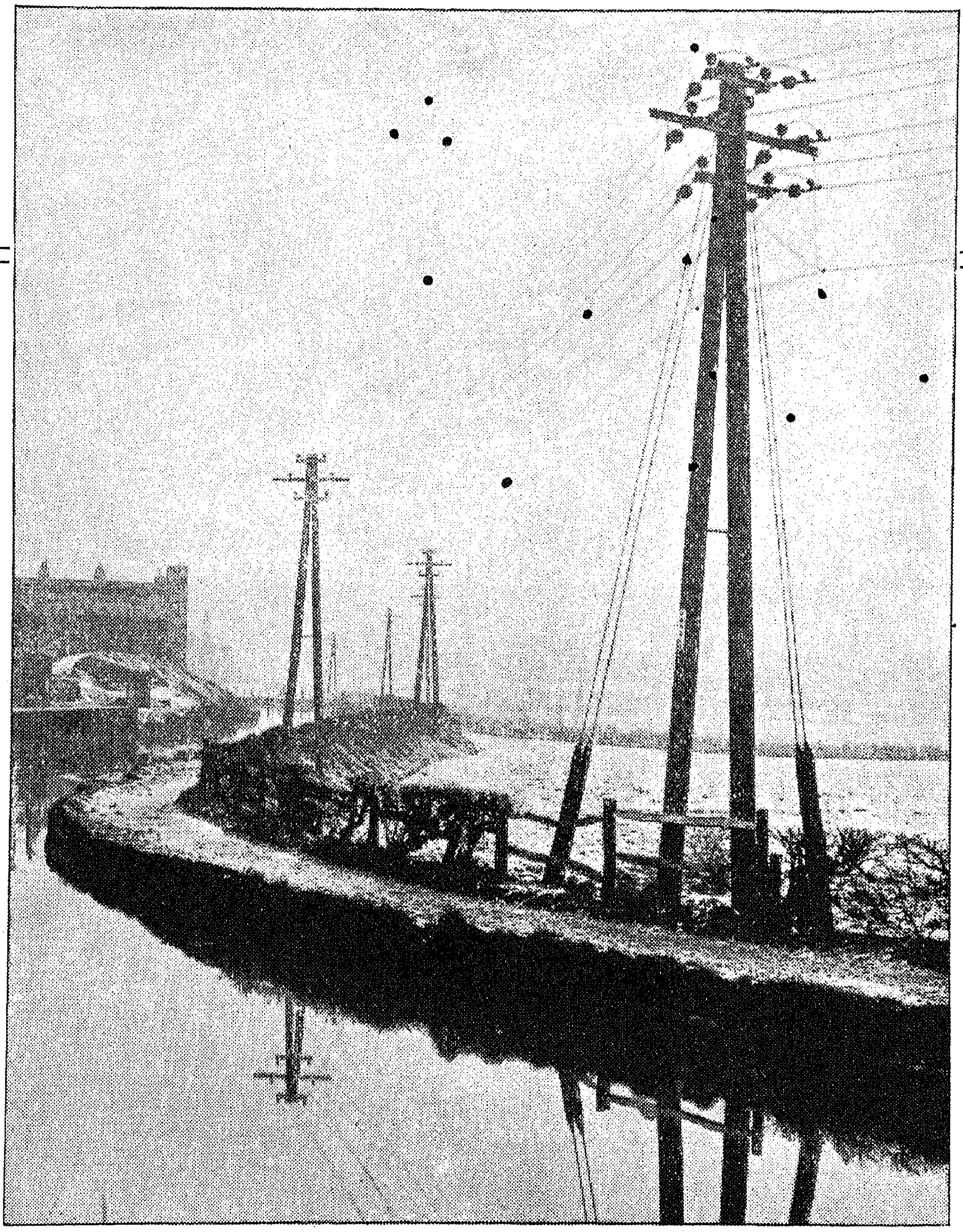
Graduate to Associate Member

Alexander, George Wellington, B.Sc.
Badhe, Balwant Jagannath, M.Sc.
Barnard, Roy Mayne, B.Sc.
Barton, Godfrey John, B.Sc.
Bell, Edward, B.Sc.
Boag, David James W., B.Sc.(Eng.).
Boul, John Edward.
Butler, Albert Edward.
Care, Norman.
Chakravarti, Nripendra Nath.
Challans, Benjamin William S., M.Sc.(Eng.).
Chapman, Reginald Henry, B.Sc.
Cook, Joseph Stanley.
Fisher, Lewis.
Fleming, Jack Morris, M.A., B.Sc.Tech.
Hamid, Abdul.
Hayter, Desmond Edward.
Heaton, William James, B.Eng.
Holmes, Douglas.
Howarth, Thomas.
Johnson, William James, B.Eng.
Lee, Walter Herbert.
Lord, Cecil Grundy.
McLauchlan, James Romans, B.Sc.(Eng.).
Marshall, Arthur Richard, B.Sc.(Eng.).
Mott, John Edward.
Muir, Robert Ballantine, Lieut., R.E., B.Sc.(Eng.).
Parkin, Frank Leslie, B.Sc. (Eng.).
Peebles, George James.
Perkins, William Stanley.
Pointer, Jack.
Rajanayagam, Sabapathippillai, B.Sc.
Roden, Alfred Henry.
Rudd, Charles Henry.
Rutherford, John Gladstone, B.Sc.
Stanesby, Harold.
Tanner, Basil Charles.
Thomas, William James T.
Walter, Charles Lockhart.
Whitney, John Stuart.
Yates, John.
Young, Ian Falconer.
Young, Norman James.

Student to Associate

Bojesen, Carl Christian.
Oram, John Edward.
Rajaratnam, Eliathamby.

Where spans are short...



THE advantage of the high strength of S.C.A. is not always essential, and in cases where spans are limited the most economical conductor is one of PLAIN ALUMINIUM. The line illustrated has been in service in the Midlands since 1917, and amply demonstrates the reliability of plain aluminium conductors for short span construction.

THE
British Aluminium
CO. LTD

Head Office: ADELAIDE HOUSE, LONDON, E.C.4.

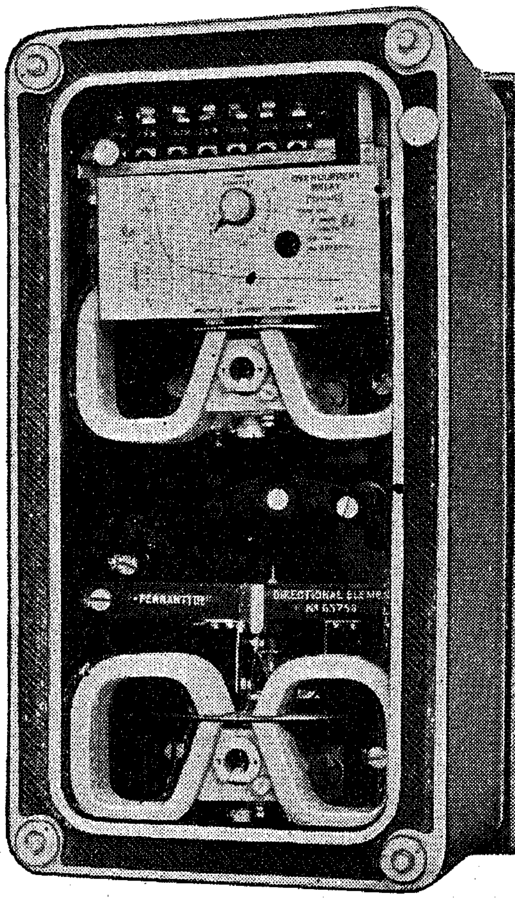
Telephone: Mansion House 5561 (6 lines). Telegrams: Cryolite, London.

I.E.E. 6 37.

Ferranti

A.C. OVERCURRENT RELAYS

F.I.25.



TYPE OD

OVERCURRENT DIRECTIONAL

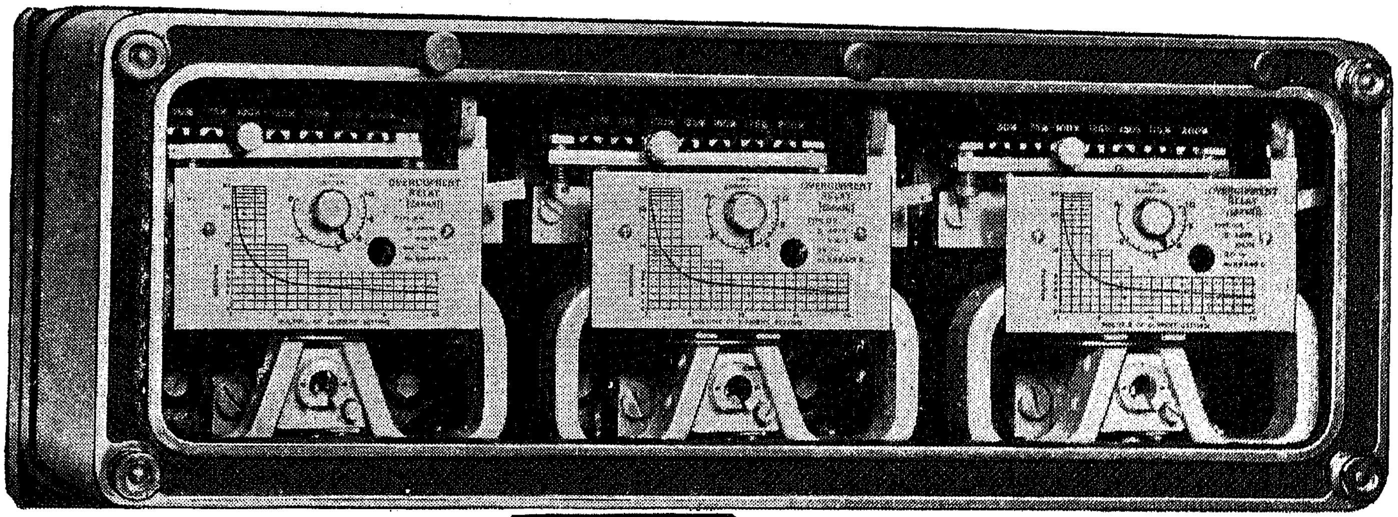
Specify Ferranti relays for the protection of your system.

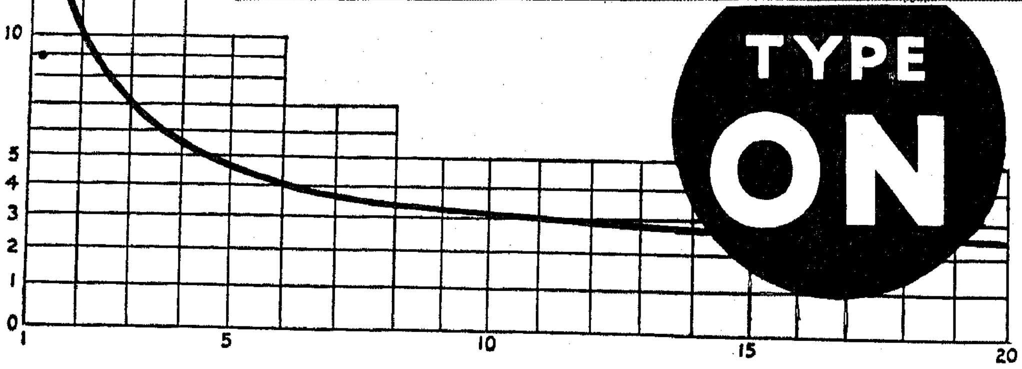
These relays have an adjustable inverse and definite minimum time limit characteristic. They are applicable both for overcurrent and earth leakage protection on A.C. circuits.

Low consumption of only 2.0 V.A. on the 100% setting imposes a very small burden on the current transformers.

High torque ensures good setting values and freedom from sticking. Heavy gauge windings withstand the severest duties. Two powerful damping magnets on each element. Contacts are exceptionally robust.

Type O.D. Relays remain truly directional down to 1% of normal voltage.





TYPE ON

OVERCURRENT NON-DIRECTIONAL

The automatic plug setting board is easily visible. Insulated tapping plug provided. Flag indicator on each element reset by hand from outside the case.

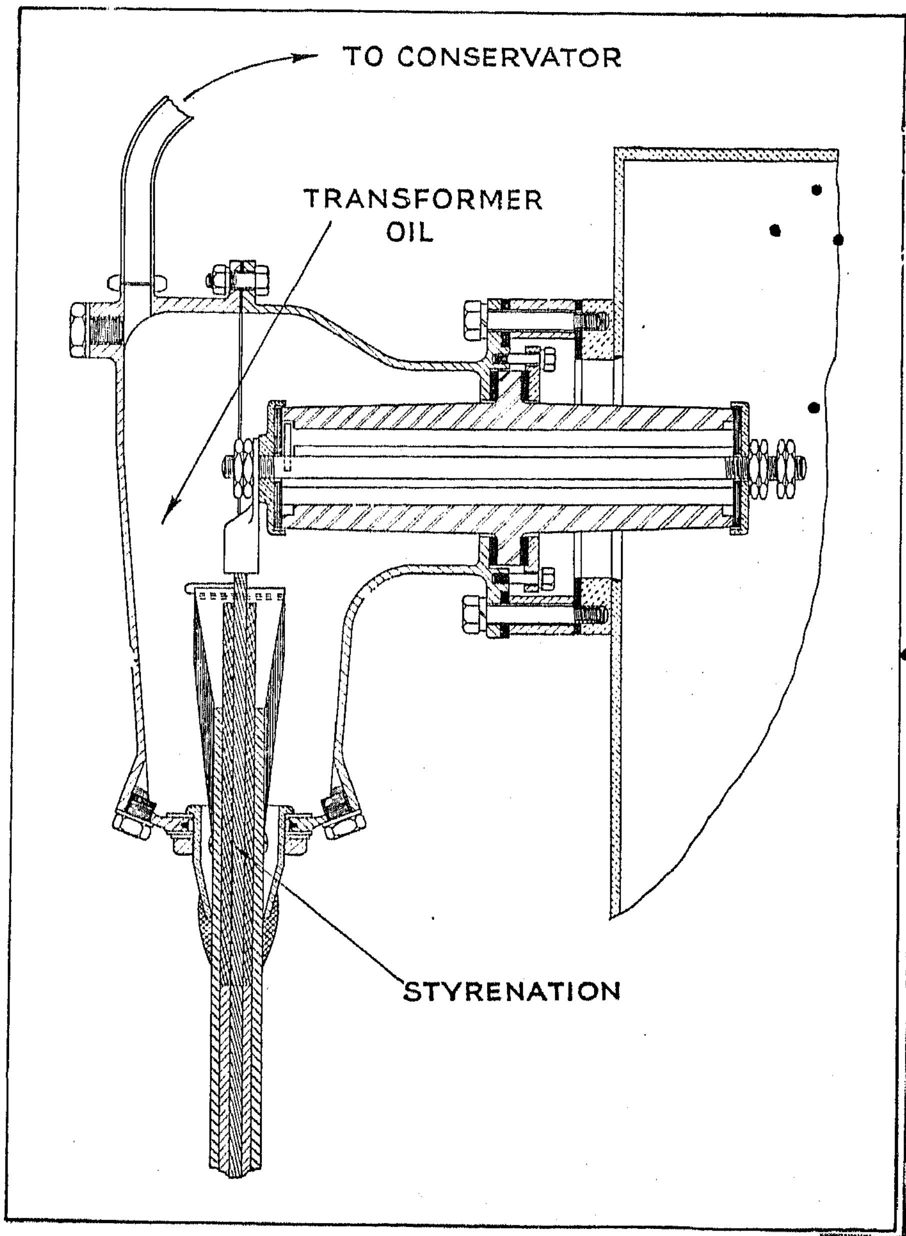
Type O.N. Relays are available in single, double and triple pole cases for horizontal or vertical mounting.

For full details write for list I.R.I.

FERRANTI LTD., HOLLINWOOD, LANCS. London Office: Bush House, Aldwych, W.C.2.

STYRENATION

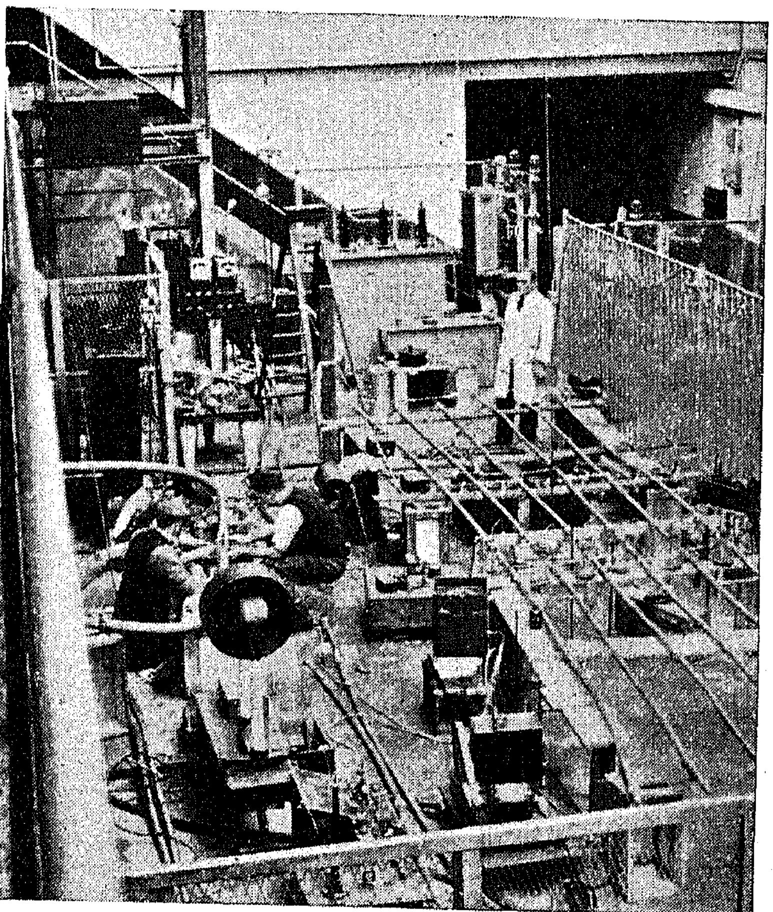
NO. I FOR TRANSFORMER & SWITCHGEAR TAILS



Styrenated Transformer Tail.

As a complement to styrene barrier joints we have developed styrene "plugs" for single core and three core cables. These "plugs" produce barrier joint effects as far as migration of compound is concerned without introducing actual joints.

An example of the above technique is the incorporation of a styrene "plug" in one end of a tail cable leading from a transformer. This enables the transformer end boxes to be filled with transformer oil working under the conservator system and eliminates all troubles due to compound expansion, contraction, leakage, etc.



Styrenation of Cable Tails in Factory.

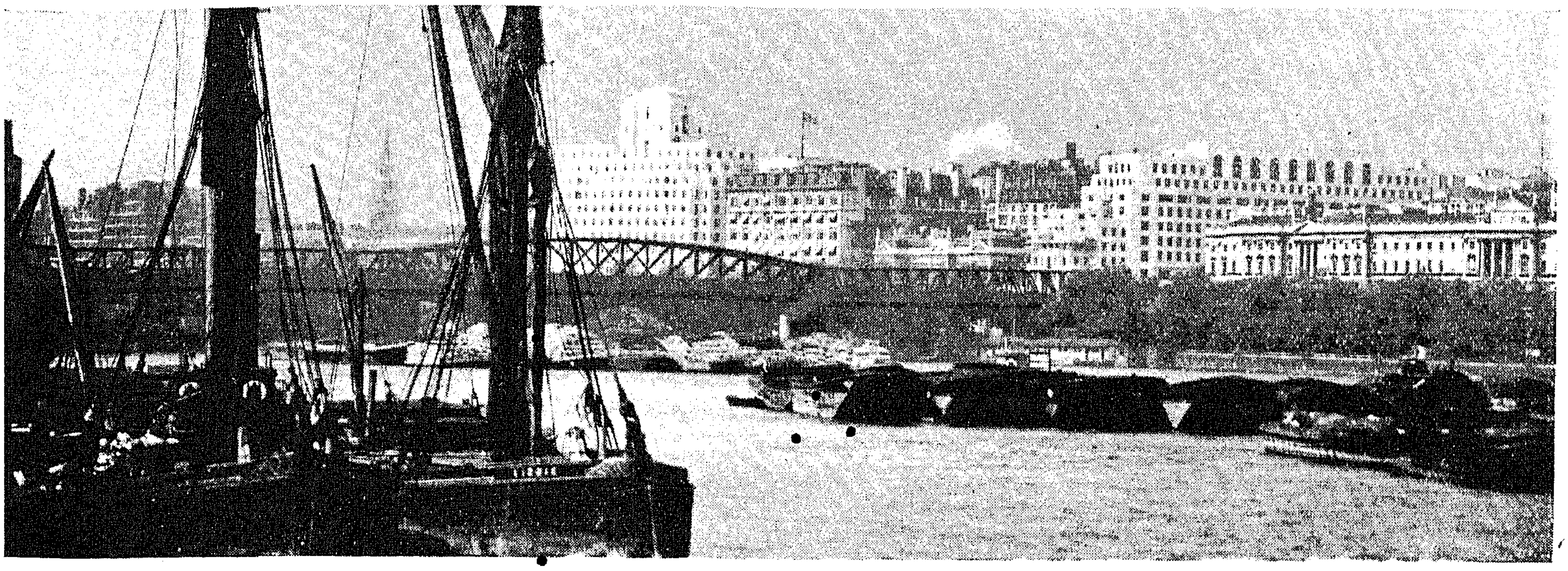
Submit your enquiries and problems to :

Standard Telephones and Cables Limited

NORTH WOOLWICH LONDON, E.16

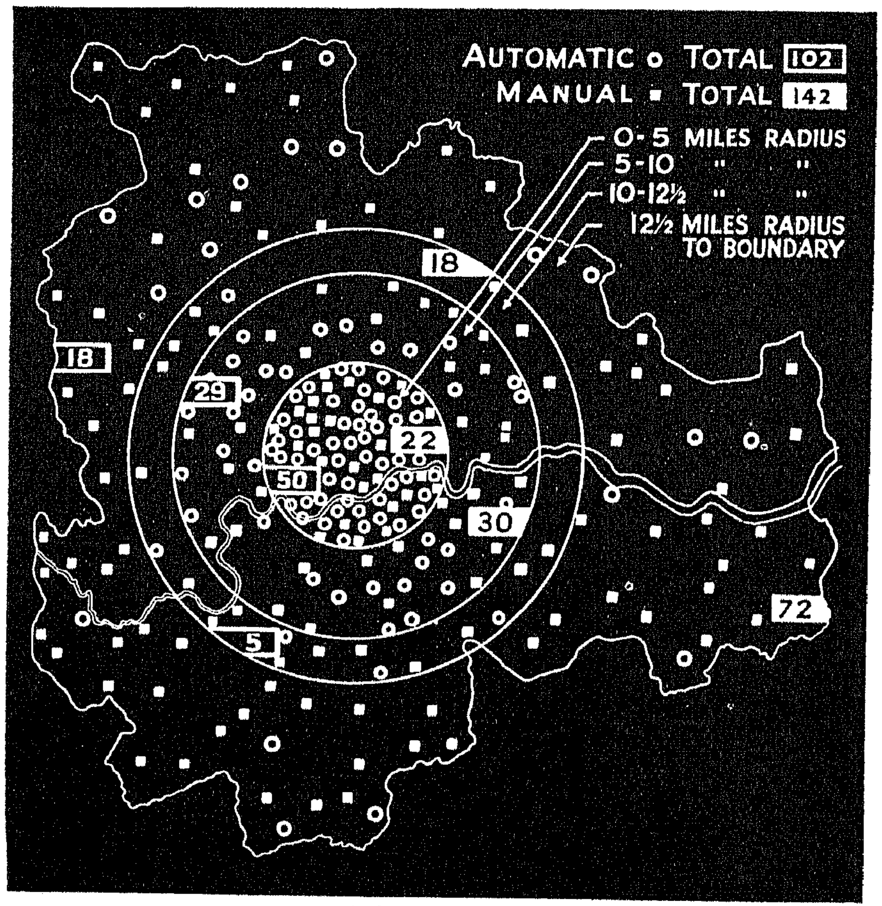
Telephone: Albert Dock 1401

BRANCHES AND REPRESENTATIVES THROUGHOUT THE WORLD

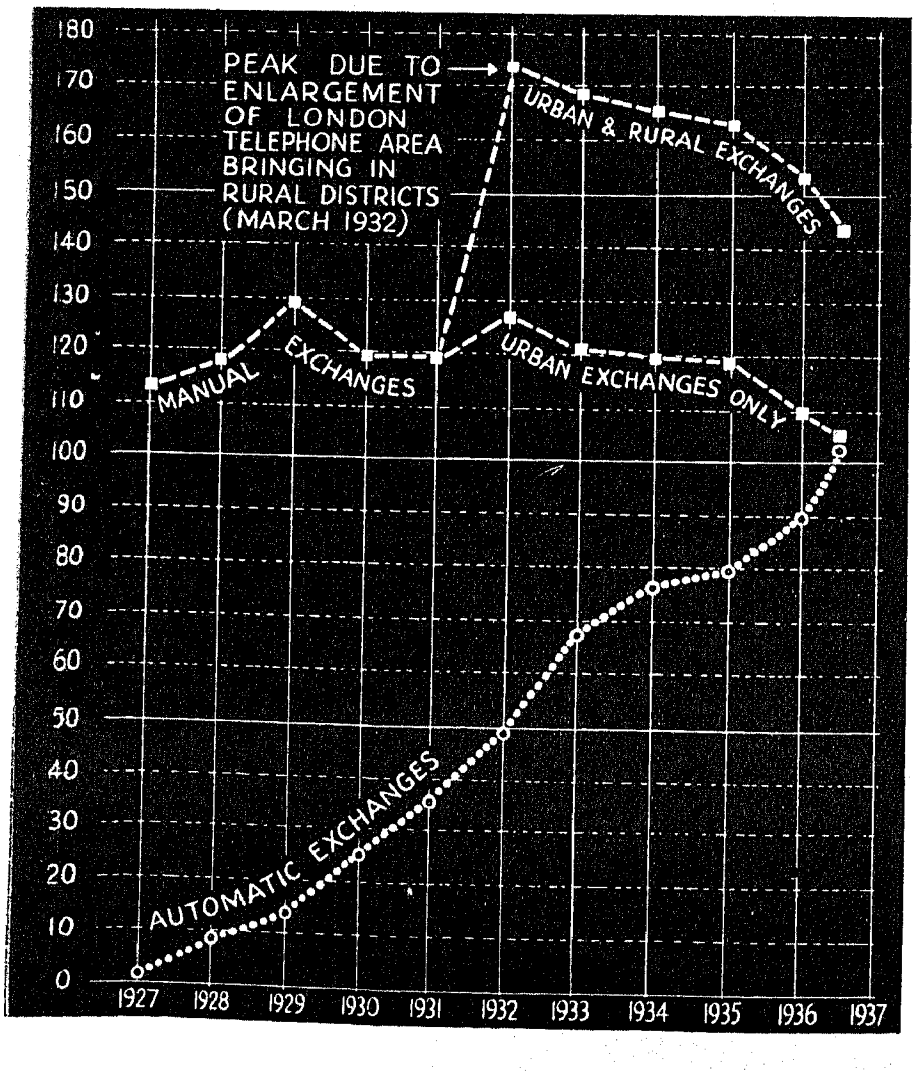


CHANGING LONDON OVER..

WHEN man first discovered that the River Thames could be forded at that spot the tale of London commenced, and since then it has been nearly 2,000 years in the telling. London River—as the sailors call it—has always figured prominently in the story, for the port made the capital, although the capital has since helped the port to flourish. That London is the financial centre of the world is largely due to the volume and importance of the port's trade. Export and import values, for example, total some £450,000,000 per year—and this figure represents, not one or two specialized commodities, but the trade of the nation. Goods to and from every country are constantly entering or leaving the port, and consequently the Bill of Exchange on London is negotiable all over the world.



Telephone Exchanges in the Greater London Area.



Chief port—centre of finance—seat of Government—in this great City telephone service must be of the highest possible standard. Only automatic telephone equipment can achieve the consistent speed and accuracy necessary, and the British Post Office some years ago standardised the Strowger system for all future use. The process of automatisation, and the growth of London's telephone communication facilities generally, are depicted on the Charts.

AUTOMATIC TELEPHONE AND ELECTRIC CO., LTD.

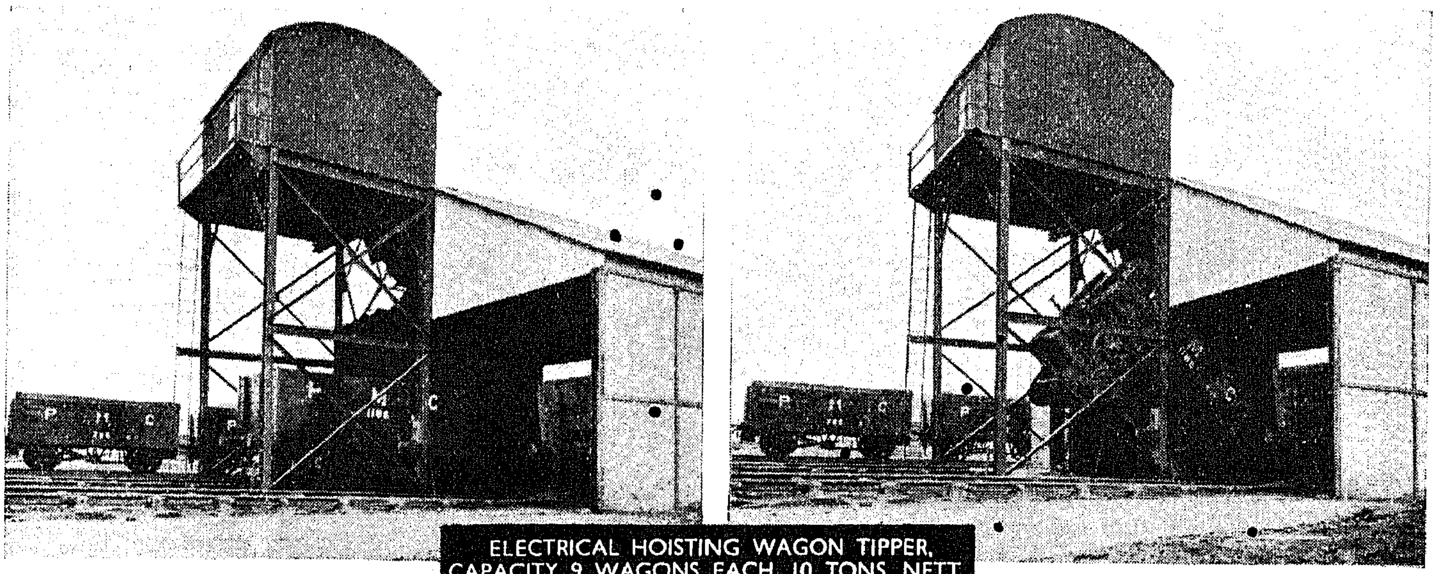
MELBOURNE HOUSE, ALDWYCH, W.C.2
Tel.: TEMPLE BAR 4506
'Grams: "STROWGER, ESTRAND LONDON"

Export Office: Norfolk House,
Norfolk Street, W.C.2
Tel.: Temple Bar 9262
'Grams: "Autelco Estrand"

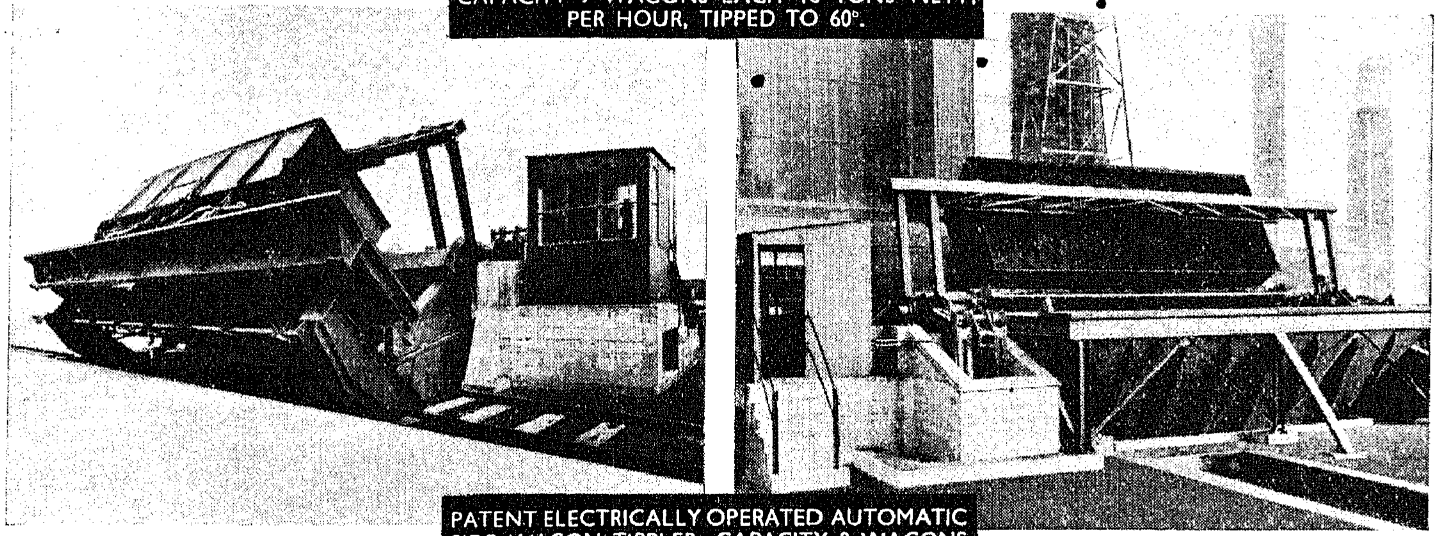
Strowger Works: Liverpool 7
Tel.: Old Swan 830
'Grams: "Strowger, Liverpool"

THE STROWGER DIAL ROTATES WITH THE WORLD

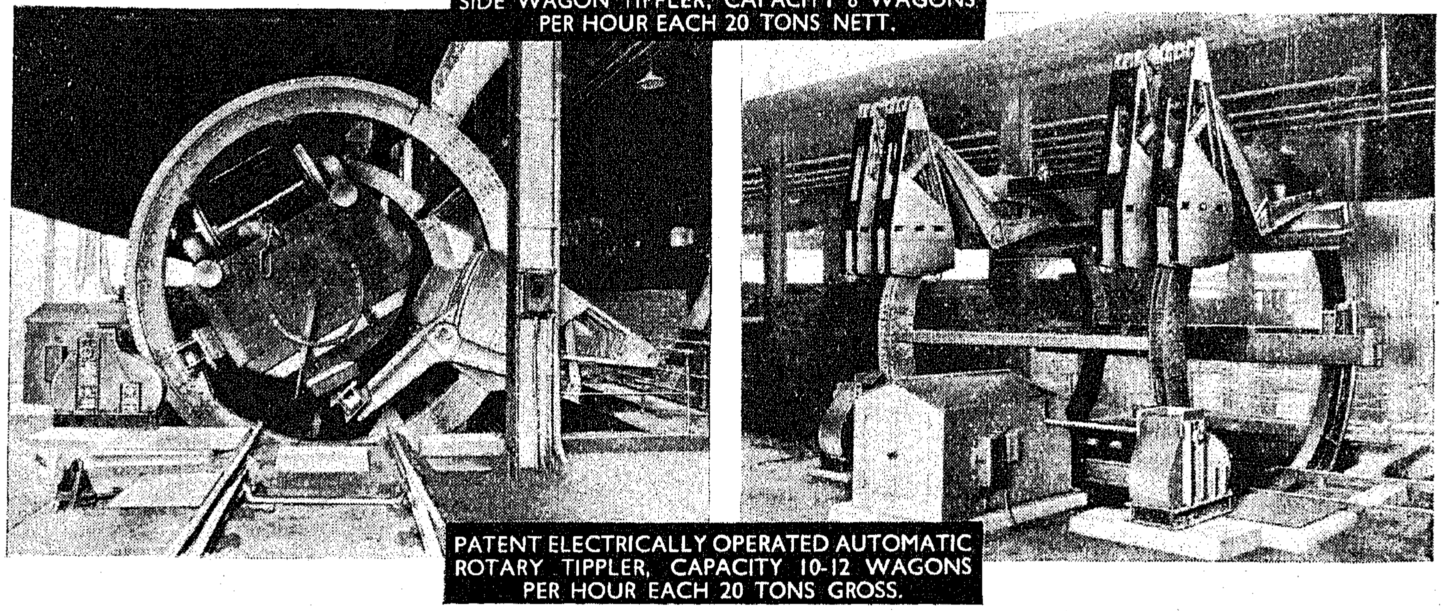
BABCOCK WAGON TIPPERS AND TIPPLERS



ELECTRICAL HOISTING WAGON TIPPER, CAPACITY 9 WAGONS EACH 10 TONS NETT. PER HOUR, TIPPED TO 60°.



PATENT ELECTRICALLY OPERATED AUTOMATIC SIDE WAGON TIPPLER, CAPACITY 8 WAGONS PER HOUR EACH 20 TONS NETT.



PATENT ELECTRICALLY OPERATED AUTOMATIC ROTARY TIPPLER, CAPACITY 10-12 WAGONS PER HOUR EACH 20 TONS GROSS.

BABCOCK & WILCOX LTD. specialise in conveying equipment for all classes of bulk materials, and, whilst such materials are many and varied, coal and minerals are the principal. The rapid discharge of railway wagons containing such materials with the least possible delay can be performed in a variety of ways, depending on the conditions at site and the class of wagon to be discharged.

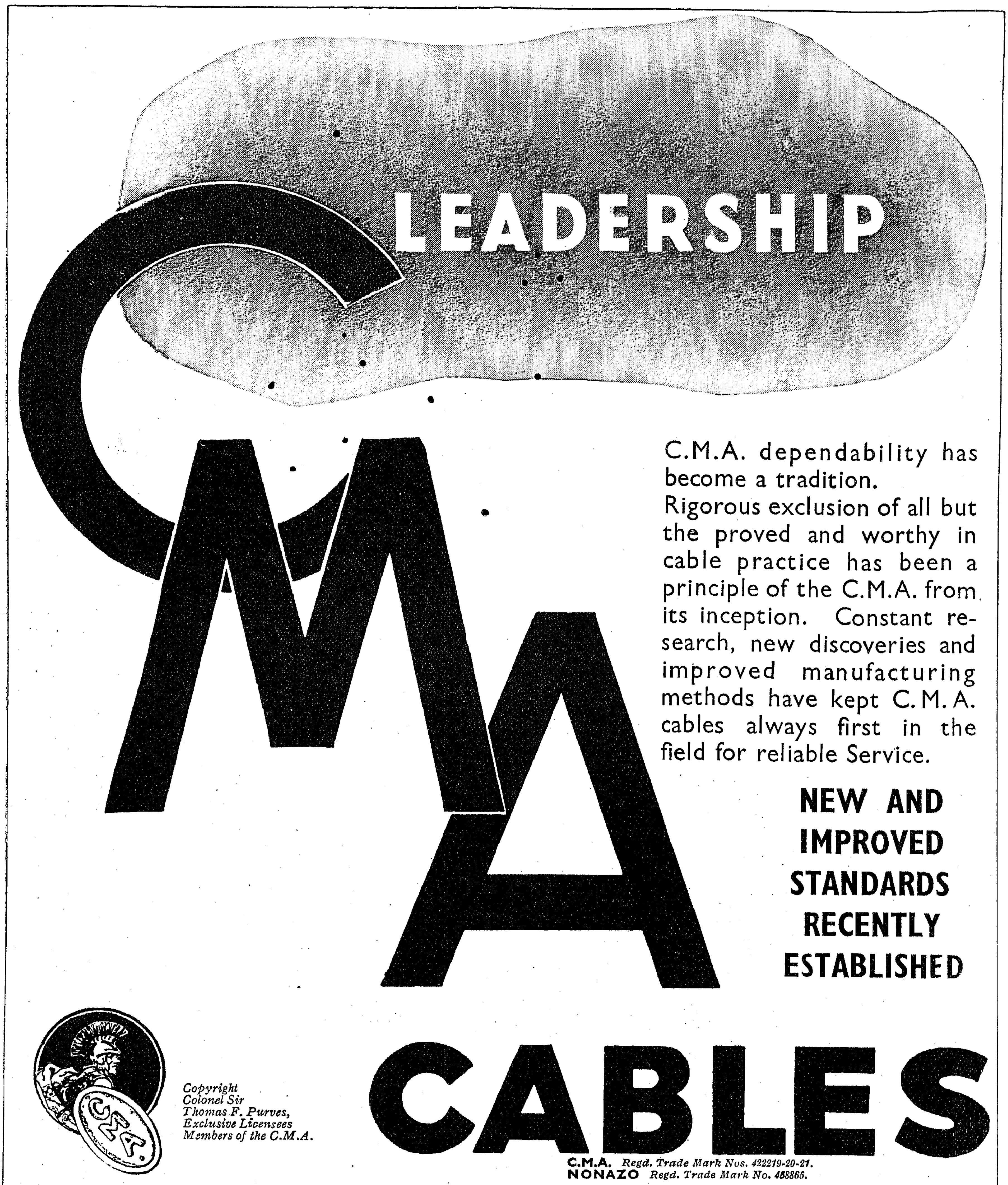
The illustrations show recent installations of an end tipper, an automatic side tippler and an automatic rotary tippler. Other devices are manufactured for covered wagons and to suit special conditions—such as combined hoists and tippers.

A recent publication, **No. 1218 — Railway Wagon Discharging Appliances,** will be sent on request.

BABCOCK & WILCOX LTD.

BABCOCK HOUSE, 34 FARRINGDON STREET, LONDON, E.C.4

Rytac



C.M.A. dependability has become a tradition. Rigorous exclusion of all but the proved and worthy in cable practice has been a principle of the C.M.A. from its inception. Constant research, new discoveries and improved manufacturing methods have kept C. M. A. cables always first in the field for reliable Service.

NEW AND IMPROVED STANDARDS RECENTLY ESTABLISHED

Copyright Colonel Sir Thomas F. Purves, Exclusive Licensees Members of the C.M.A.

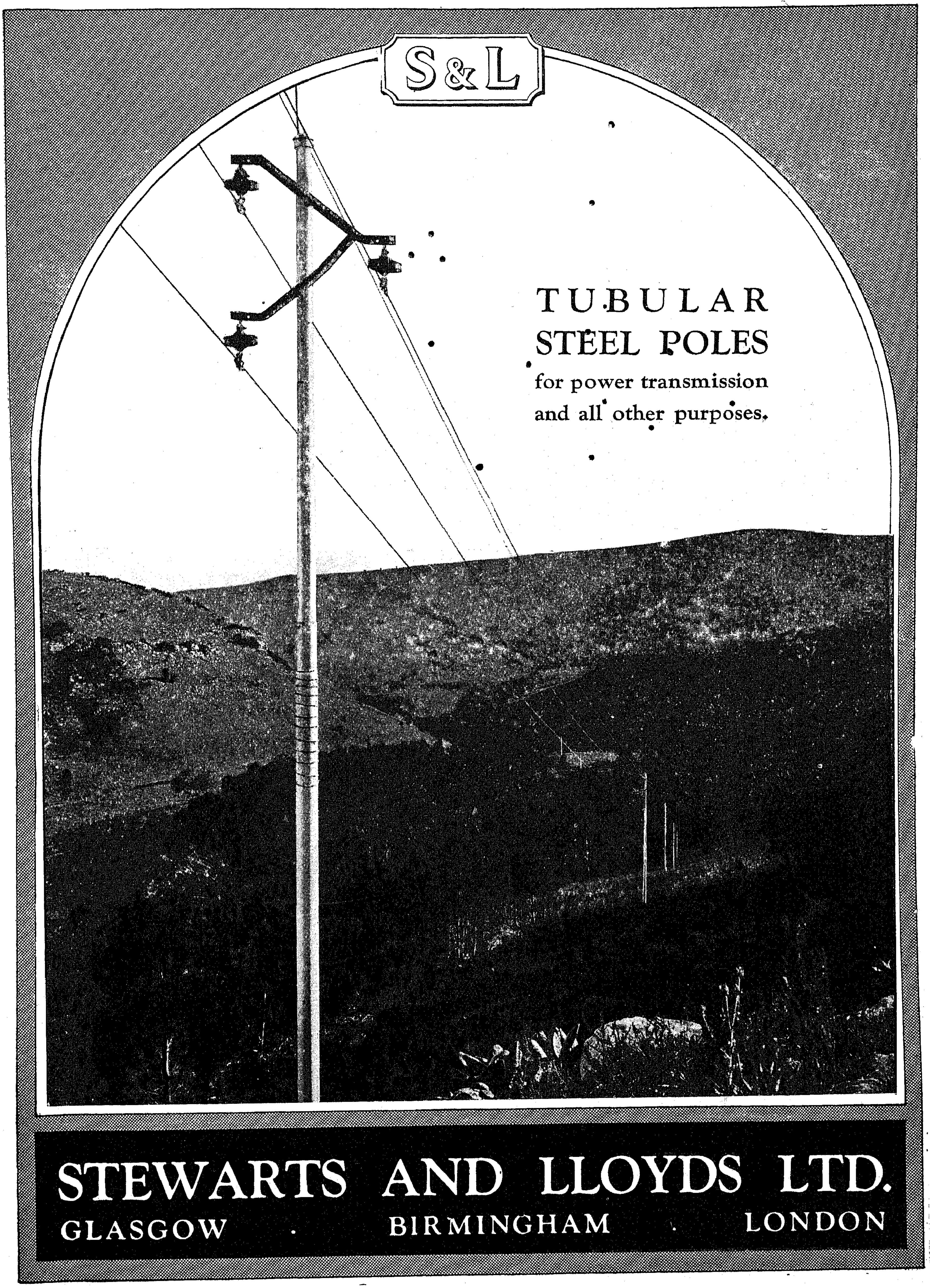
CABLES

C.M.A. *Regd. Trade Mark Nos. 422219-20-21.*
NONAZO *Regd. Trade Mark No. 458865.*

MEMBERS OF THE C.M.A.

The Anchor Cable Co. Ltd.
British Insulated Cables Ltd.
Callender's Cable & Construction Co. Ltd.
The Craigpark Electric Cable Co. Ltd.
Crompton Parkinson Ltd. (Derby Cables Ltd.)
Edison Swan Cables Ltd.
The Enfield Cable Works Ltd.
Greengate & Irwell Rubber Co. Ltd.
W. T. Glover & Co. Ltd.
W. T. Henley's Telegraph Works Co. Ltd.
The India Rubber, Gutta-Percha & Telegraph Works Co. Ltd (The Silvertown Co.)
Johnson & Phillips Ltd.
Liverpool Electric Cable Co. Ltd.
The London Electric Wire Co. and Smiths Ltd.
The Macintosh Cable Co. Ltd.
Pirelli-General Cable Works Ltd. (General Electric Co. Ltd.)
St. Helens Cable & Rubber Co. Ltd.
Siemens Brothers & Co Ltd. (Siemens Electric Lamps & Supplies Ltd.)
Standard Telephones & Cables Ltd.
Union Cable Co. Ltd.

Advert. of the Cable Makers' Association, Sardinia House, Sardinia Street, Kingsway, London, W.C.2. Telephone Holborn 4976



S&L

TUBULAR
STEEL POLES
for power transmission
and all other purposes.

STEWARTS AND LLOYDS LTD.
GLASGOW . BIRMINGHAM . LONDON

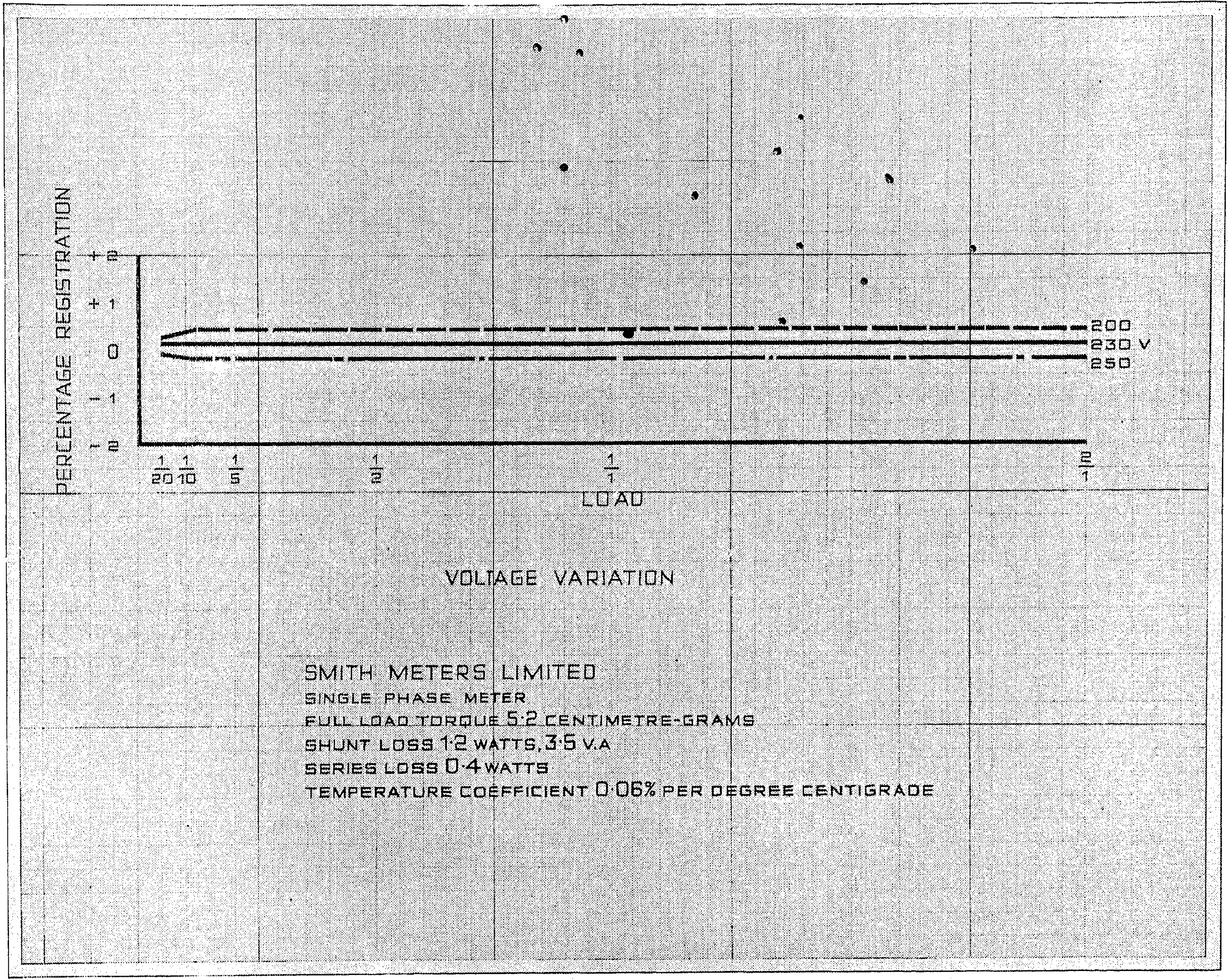
COMPENSATION FOR VOLTAGE VARIATION

The last lamination in the Smith Meter has a specially designed complete stamping carrying a by-pass for some of the voltage flux. This by-pass being constantly saturated, takes a definite amount from the effective voltage flux, and this amount is, therefore, a smaller proportion of the total flux as the voltage rises. Therefore, the proportional torque is maintained for different supply voltages. THIS FEATURE ENABLES US TO UTILISE A STRONG POTENTIAL FLUX FOR TORQUE PURPOSES.

SMITH METER
SINGLE PHASE

SMITH METERS LTD., ROWAN ROAD, STREATHAM VALE, S.W.16. POLLARDS 2271. *Manufactured under Smith and Angold Patents.*

INFALLIBLE ACCURACY AT ANY SUPPLY VOLTAGE...



★APPROVED BY THE ELECTRICITY COMMISSIONERS

. . . the Electricity Commissioners approve of the construction and pattern of the meter for the measurement of electrical energy when supplied on the constant pressure two wire, single phase, alternating current system at a frequency of 50 cycles per second and known as the Smith Meters, Type "A," Single Phase Watthour Meter, of rated sizes . . . 200 volts to 250 volts, and 400 volts to 500 volts.

SMITH METER
SINGLE PHASE

SMITH METERS LTD., ROWAN ROAD, STREATHAM VALE, S.W.16. POLLARDS 2271. *Manufactured under Smith and Angold Patents.*

NIFE . NEVERFAYLE

EMERGENCY EQUIPMENT

INSTALLED IN THE

SHAKESPEARE MEMORIAL THEATRE

STRATFORD - ON - AVON

- **Occupies 40% less space than other types.**

Incorporates NIFE Steel Plate Alkaline Battery—practically indestructible.

No corrosive fumes.

Complies with Latest Home Office Regulations.

- **Over 50 sets ordered this year.**

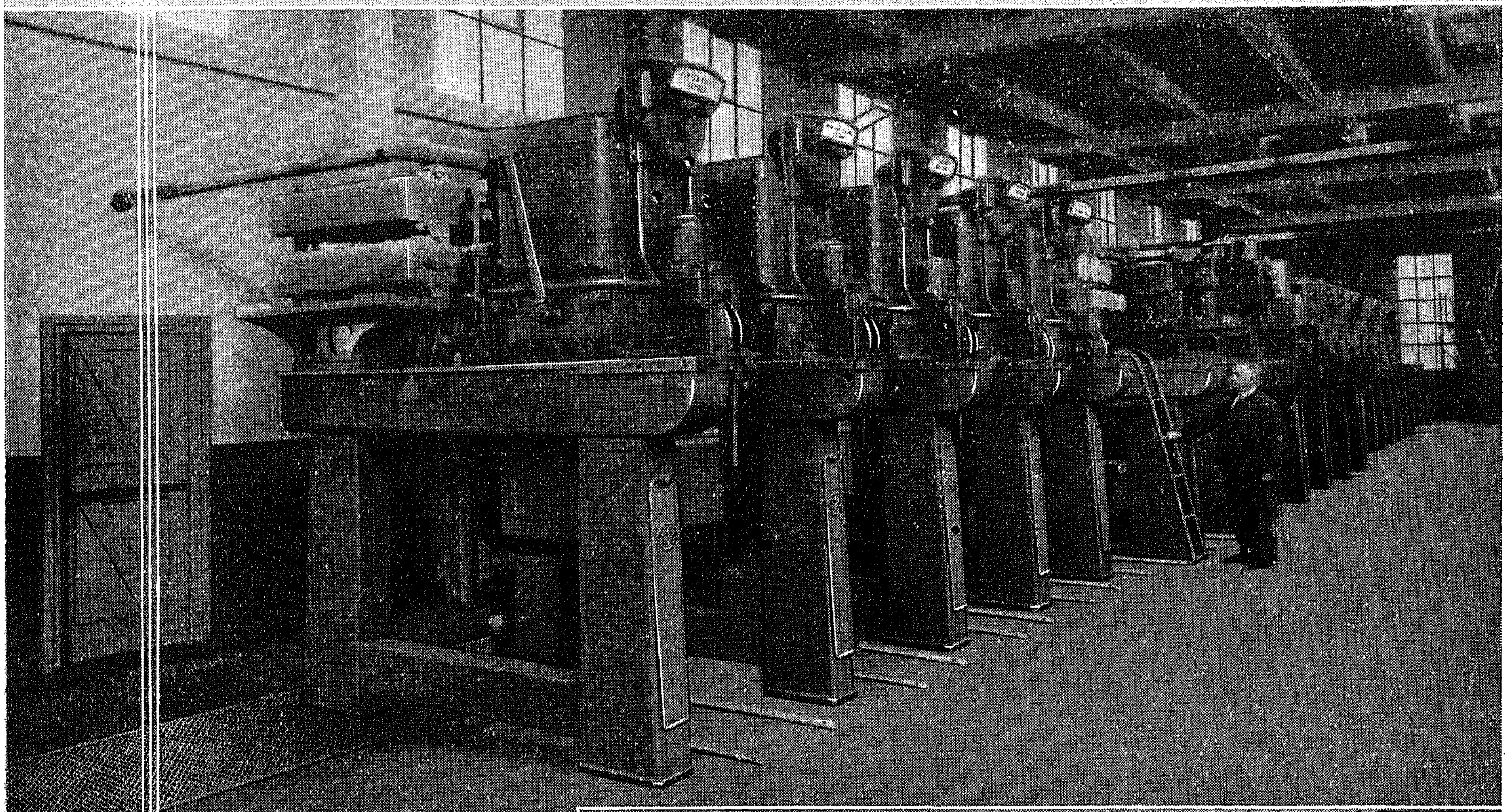
Numerous schemes are available, write for details.

NI-FE ACCUMULATOR

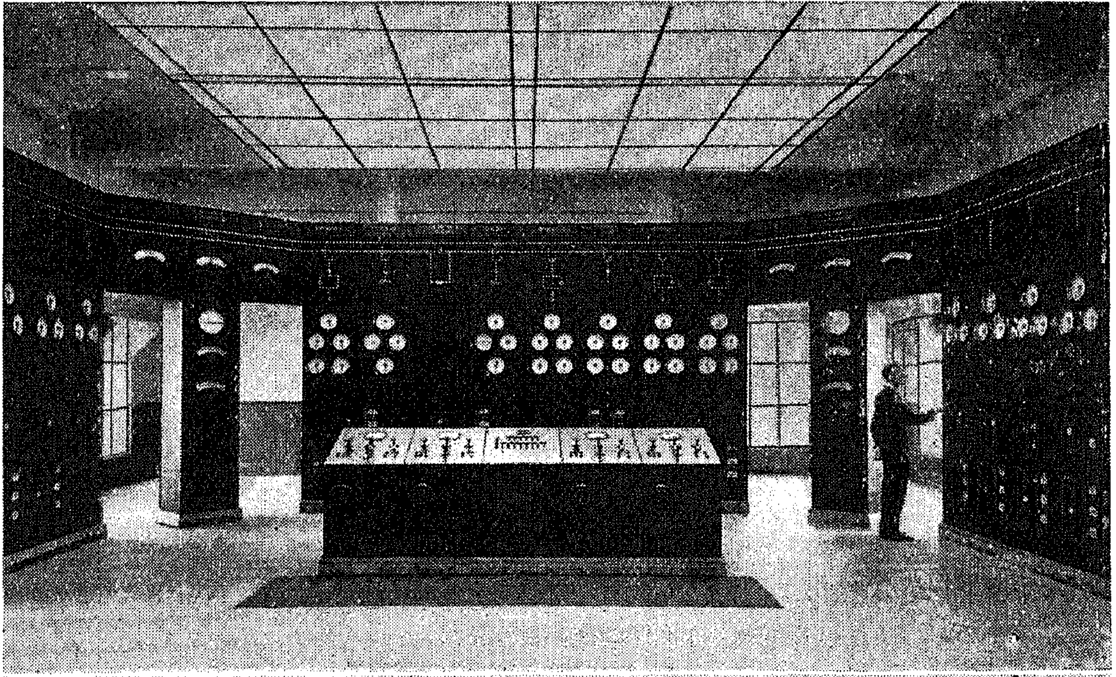
BATTERIES LIMITED

HUNT END WORKS REDDITCH

WATFORD METAL-CLAD SWITCHGEAR



Main 6,600 Volt "Metrovick" types K4C and K5C Horizontal drawout duplicate bus metal-clad Switchgear installed at Watford Generating Station



Control Room showing panels and generator control desks.

METROPOLITAN Vickers
ELECTRICAL CO. LTD.
TRAFFORD PARK . . . MANCHESTER 17

METROVICK ELECTRIC DISCHARGE LAMPS *for* SATISFACTORY LIGHTING

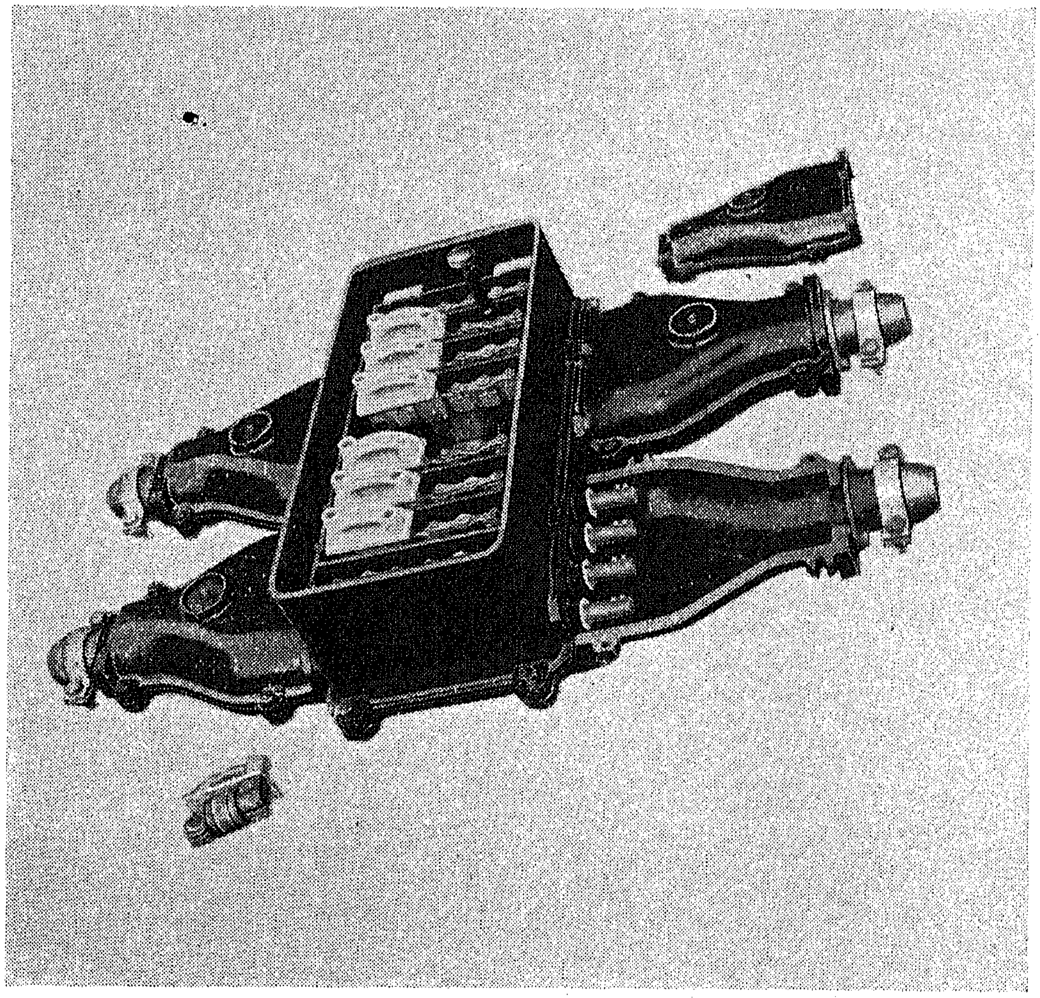
F/K 701

TENNYSON and B.I. PRODUCTS

He wrote:

"I ADMIRE JOINTS OF CUNNING WORKMANSHIP"

" The Vision of Sin."—Tennyson.



(British Pat. Nos. 326,332 ; 404,057 ; 355,129)

We cannot say whether the great Poet Laureate would have admired the cunning workmanship of B.I. underground joint boxes, but his words are strangely apt and express the views of hundreds of engineers.

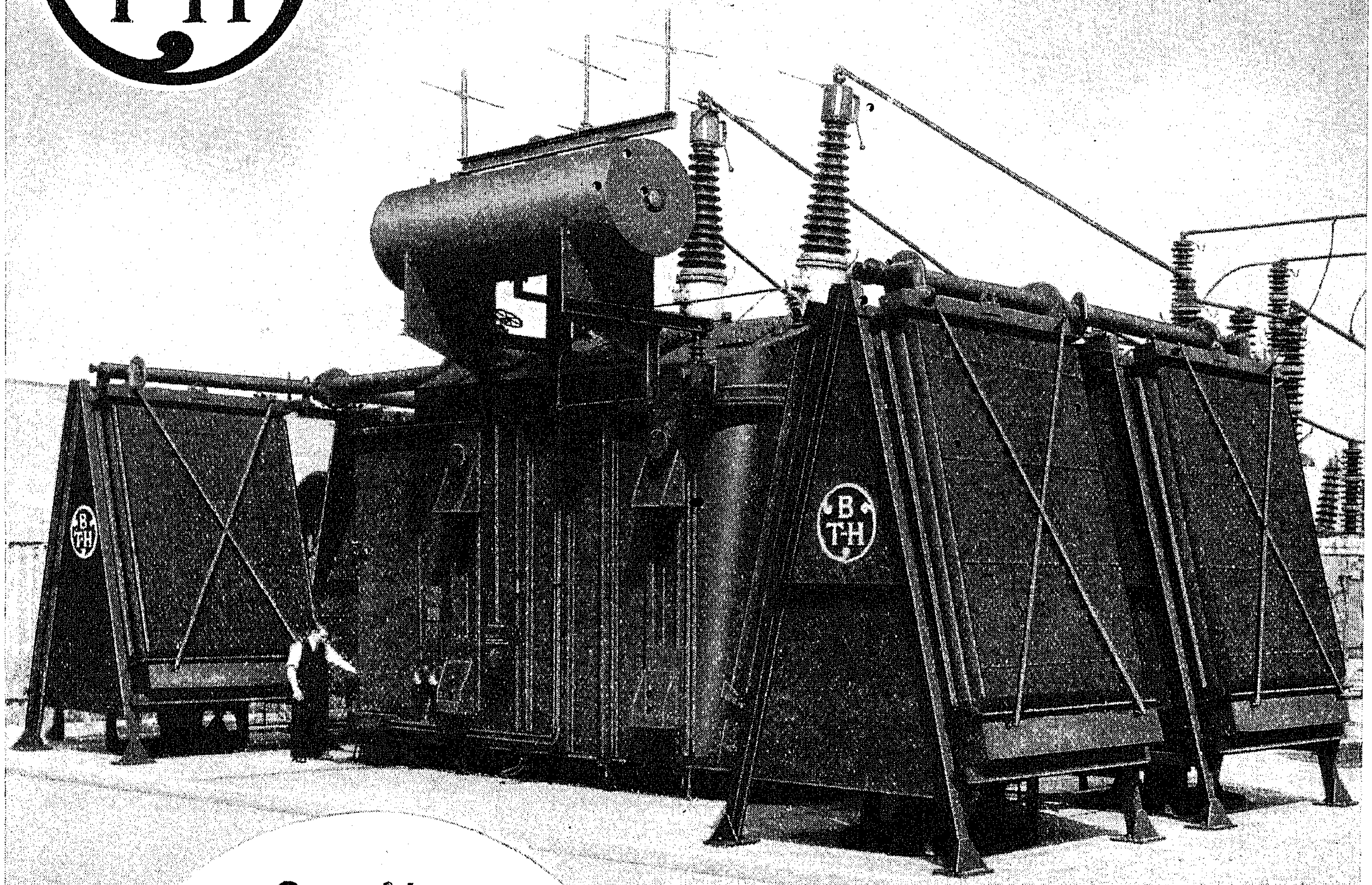
Here is the latest **B.I. " Detachable Pocket " Type Box** which is so useful in laying out the distribution system of a growing network.

You don't need to lay all the cables at once. If a 4-way box is installed and only two cables jointed up, other cables can always be added without disturbing the original cables or box, or interrupting the supply. Cunning workmanship expresses it exactly.

BRITISH INSULATED CABLES LTD., PRESCOT, LANCS.

Tel. No. Prescot 6571. *London Office*, Surrey House, Embankment, W.C. 2. Tel. No. Temple Bar 7722.

B T-H TRANSFORMERS



One of two BTH 45 MVA., 132/33 KV., 3-phase, 50 cycle, ON/OB Power Transformers installed at the Transforming Substation, Roath, Cardiff.

● ● ●

Central Electricity Board

We make ALL Types of TRANSFORMERS

BTH RUGBY

THE BRITISH THOMSON-HOUSTON COMPANY LIMITED, RUGBY, ENGLAND.

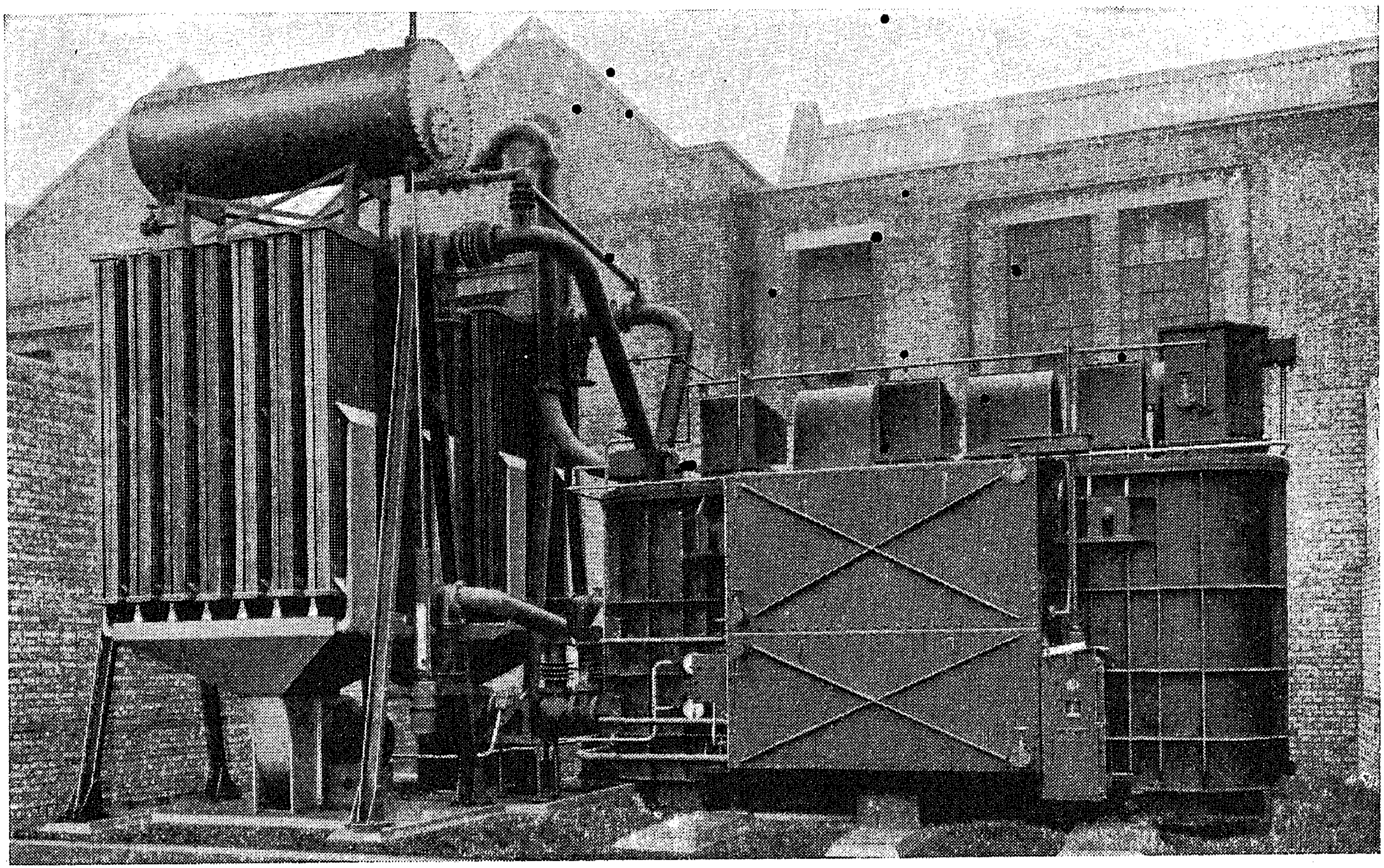
A2374

ASSOCIATED ELECTRICAL INDUSTRIES LTD. AEI

LIST OF ADVERTISERS IN THIS ISSUE

	PAGE
Automatic Coil Winder & Electrical Equipment Co., Ltd.	xvii
Automatic Telephone & Electric Co., Ltd.	iv
Babcock & Wilcox, Ltd.	v
Batteries, Ltd.	x
British Aluminium Co., Ltd.	i
British Insulated Cables, Ltd.	xii
British Thomson-Houston Co., Ltd.	xiii
Cable Makers' Association	vi
Chamberlain & Hookham, Ltd.	xvii
English Electric Co., Ltd.	xv
Ferranti, Ltd.	ii
Liverpool Electric Cable Co., Ltd.	xvi
London Electric Wire Co. & Smith's Ltd.	xvi
Metropolitan-Vickers Electrical Co., Ltd.	xi
Nalder Brothers & Thompson, Ltd.	xvii
Smith (Frederick) & Co.	xvi
Smith Meters, Ltd.	viii & ix
Standard Telephones & Cables, Ltd.	iii
Stewarts & Lloyds, Ltd.	vii
Westinghouse Brake & Signal Co., Ltd.	xviii
Zenith Electric Co., Ltd.	xvi

Coupling FULHAM



to the Grid

A 45MVA

132/66kV Transformer

with ON/OFB

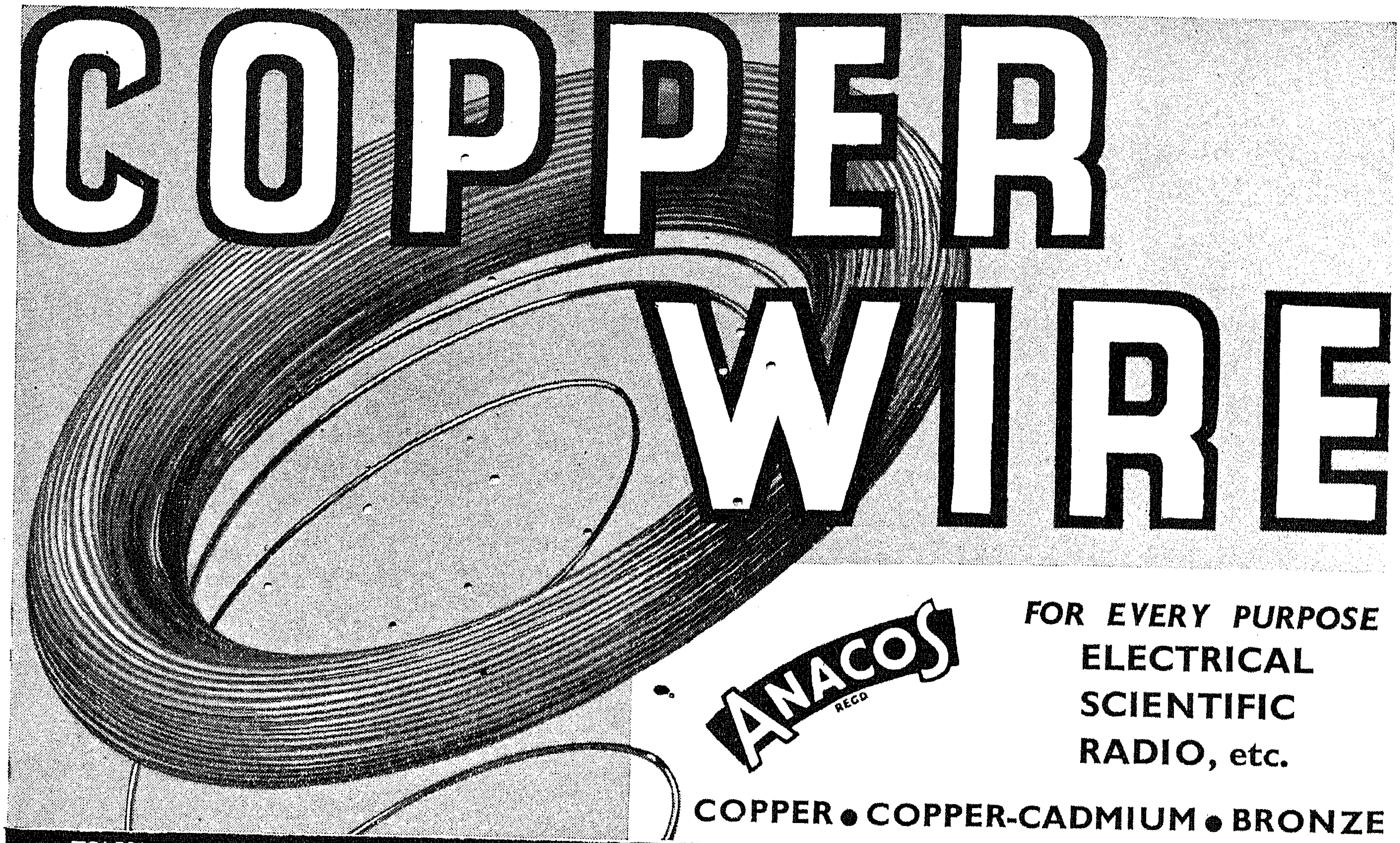
cooling

Four transformers similar to that illustrated above are being supplied to the Central Electricity Board for installation at Fulham Power Station, for coupling the 66 kV. bus-bar to the Grid at 132 kV. Connections to the transformer are made on both H.V. and L.V. sides by single-core cable.

This installation is the latest example of 'English Electric' transformers supplied to the C.E.B. It is noteworthy that the Company has supplied many units in all sizes up to 45 MVA., and voltages up to 132 kV for service in all of the C.E.B. Areas.

Write for
Pubns. Q53 & Q54A

THE
ENGLISH ELECTRIC
COMPANY LIMITED
STAFFORD - - BRADFORD - - RUGBY - - PRESTON



FOR EVERY PURPOSE
ELECTRICAL
SCIENTIFIC
RADIO, etc.

COPPER ● COPPER-CADMIUM ● BRONZE

TELEPHONE
BLACKFRIARS
8701 (8 lines)

FREDERICK SMITH & COMPANY
(INCORPORATED IN THE LONDON ELECTRIC WIRE COMPANY AND SMITHS, LIMITED)
ANACONDA WORKS, SALFORD, 3, LANCS.

TELEGRAMS
"ANACONDA
MANCHESTER"

ZENITH
(Regd. Trade-Mark)

ELECTRICITY SUPPLY (METERS) ACT, 1936

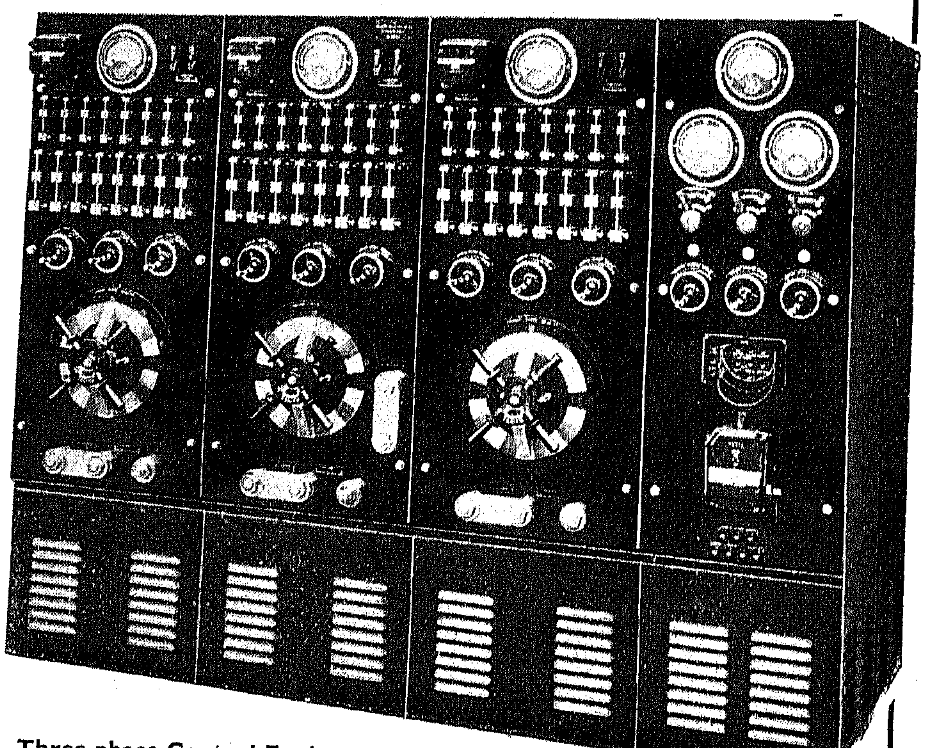
CURRENT, POTENTIAL and POWER FACTOR CONTROL APPARATUS

for METER TESTING

Equipment supplied to meet all requirements, and to comply in all respects with the provisions of the Act.

Complete sets, or components, including Current and Potential Transformers, Rheostats, Resistances, Control Gear, Phase-Shifting and Regulating Transformers, Meter Benches, etc.

Quotations and suggestions gladly forwarded on request.



Three-phase Control Equipment.
0·05-1000 Amperes, 0-500 Volts.

THE ZENITH ELECTRIC Co. Ltd.

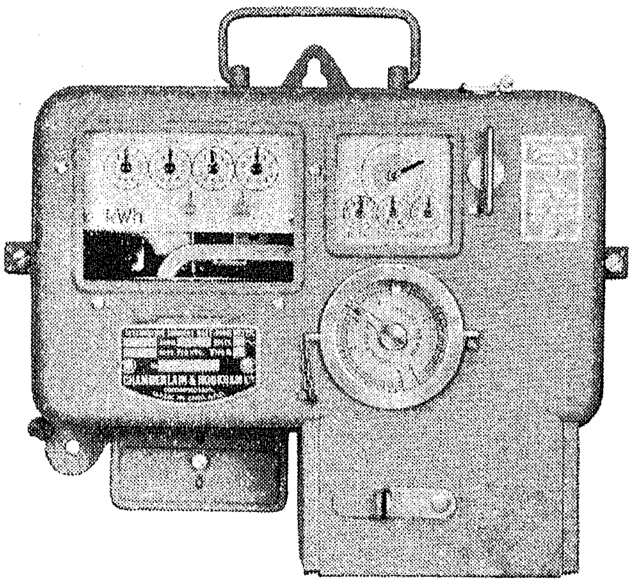
Contractors to H.M. Admiralty, War Office, Air Ministry, Post Office, Principal Electricity Undertakings, etc.

ZENITH WORKS, VILLIERS ROAD
WILLESDEN GREEN, LONDON, N.W.2

Telephone:
WILlesden 4087-8

Telegrams:
"Voltaohm, Phone, London"

A TWO PART TARIFF PREPAYMENT METER WITH STAR FEATURES

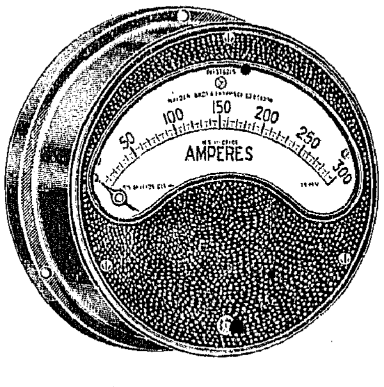


- ★ Rental charge adjustable from 2d. to 4/- in steps of ¼d. or from 4d. to 8/- in steps of ½d.
- ★ Exact amount of rental always collected.
- ★ Special arrears device enables consumer when in arrears to obtain emergency supply on payment of one coin.

Manufacturers:
CHAMBERLAIN & HOOKHAM Ltd.
SOLAR WORKS, NEW BARTHOLOMEW STREET
BIRMINGHAM
London Office: Magnet House, Kingsway, W.C.2

NALDERS

N C S



NCS Electrical Measuring instruments include switchboard, portable and recording meters, synchronisers, circuit breakers, protective relays, etc. *Full details on request.*

HYPER-SCALE INSTRUMENTS *for* SWITCHBOARDS

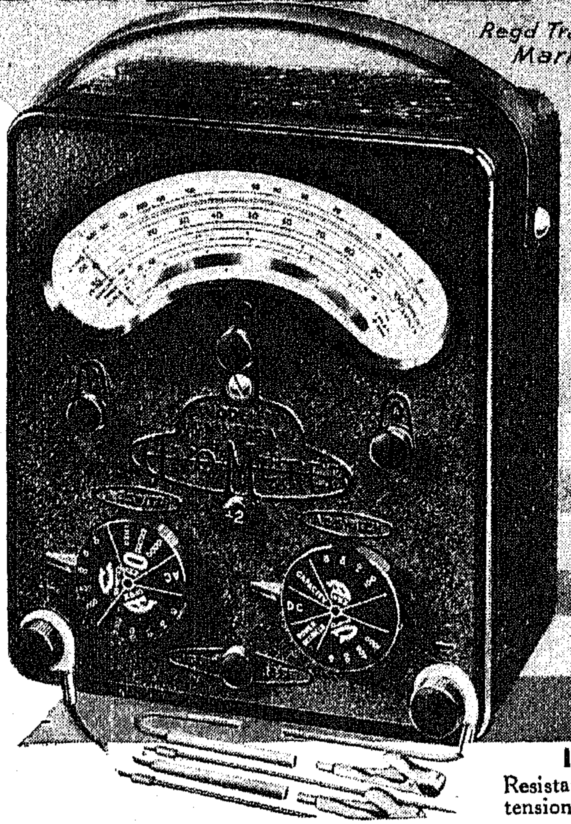
NCS Improved Dynamometer Instruments—Ammeters, Voltmeters and Wattmeters—Moving Coil or Moving Iron patterns made with 4″, 5″, 6″, or 8″ Dials and Scales. Special improvements give strength, rigidity and permanent accuracy.

NALDER BROS. & THOMPSON LTD
Dalston Lane Works, London, E.8
Telegrams: Occlude, Hack, London. Telephone: Clissold 2365 (3 lines)

The 46-RANGE UNIVERSAL AVOMETER

MODEL 7

Regd Trade Mark



The Model 7 Avometer provides unique facilities for electrical measuring. It is a compact multi-range A.C./D.C. meter, having 46 ranges which provide for all measurements of A.C. and D.C. amperes and volts, and also for measurements of capacity, audio-frequency power output and decibels.

The meter conforms to B.S. 1st grade requirements. Readings can be made with great accuracy. No external shunts or series resistances. If an overload is applied, a protective cut-out automatically disconnects the meter from the source of supply.

Write for descriptive pamphlet

THE AUTOMATIC COIL WINDER & ELECTRICAL EQUIPMENT CO., LTD.
Winder House, Douglas St., London, S.W.1
Telephone: Victoria 3404/7

EVERY Electrical Measurement

A.C. and D.C. Amperes and Volts

RESISTANCE measurements

CAPACITY, POWER, DECIBELS

BRITISH MADE

16 Gns.
Resistance Range Extension Unit (for measurements down to 1/100th-ohm) 10/-.

The 36-range Universal Avometer, 13 gns.
The 22-range D.C. Avometer, 9 gns.
Leather Carrying Cases - - £1
DEFERRED TERMS IF DESIRED.

ANOTHER INSTALLATION

WESTINGHOUSE

BATTERY CHARGERS

Part of an installation of twelve 30 cell 30 amp. chargers in use with Electricar Vehicles at the Royal Borough of Kensington Cleansing Department.

Send for a new edition of Booklet D.P.11E to Dept. I.E.E.

WESTINGHOUSE BRAKE & SIGNAL CO., LTD.,
82 YORK ROAD, KING'S CROSS, LONDON, N.1

LOCAL CENTRES AND SUB-CENTRES—*(Continued)*.

NORTH-WESTERN CENTRE.

Chairman.—G. L. PORTER.

Hon. Secretary.—L. H. A. CARR, M.Sc.Tech., "Oakleigh," Cambridge Road, Hale, Altrincham, Cheshire.

SCOTTISH CENTRE.

Chairman.—H. C. BABB.
Hon. Secretary.—R. B. MITCHELL, 53, Lauderdale Gardens, Hyndland, Glasgow, W.2.
Hon. Assist. Secretary.—H. V. HENNIKER, 172, Craigleith Road, Edinburgh.

Dundee Sub-Centre.

Chairman.—J. HARGROVE.
Hon. Secretary.—P. PHILIP, c/o Electricity Supply Dept., Dudhope Crescent Road, Dundee.

SOUTH MIDLAND CENTRE.

Chairman.—E. A. REYNOLDS, M.A.
Hon. Secretary.—H. HOOPER, 65, New Street, Birmingham.
Hon. Assist. Secretary.—R. H. RAWLL, "Clonsilla," 35, Park Hill Road, Harborne, Birmingham, 17.

East Midland Sub-Centre.

Chairman.—W. F. FURSE.
Hon. Secretary.—J. F. DRIVER, Brighton House, Herrick Road, Loughborough.

WESTERN CENTRE.

Chairman.—J. W. SPARK.
Hon. Secretary.—H. R. BEASANT, 77, Old Market Street, Bristol, 2.

West Wales (Swansea) Sub-Centre.

Chairman.—A. JARRATT.
Hon. Secretary.—R. RICHARDS, 78, Glanbrydan Avenue, Swansea.

Hampshire Sub-Centre (directly under the Council).

Chairman.—R. E. G. HORLEY.

Hon. Secretary.—A. G. HISCOCK,
25, Burbidge Grove, Southsea, Hants.

Northern Ireland Sub-Centre (directly under the Council).

Chairman.—T. T. PARTRIDGE.

Hon. Secretary.—W. J. McC. GIRVAN,
Ardkeen, McCaughan Park, Lower Castlereagh, Belfast.

INFORMAL MEETINGS.

Chairman of Committee.—F. JERVIS SMITH.

METER AND INSTRUMENT SECTION.

Chairman.—G. F. SHOTTER.

TRANSMISSION SECTION.

Chairman.—P. DUNSHEATH, O.B.E., M.A., D.Sc.

WIRELESS SECTION.

Chairman.—E. MALLETT, D.Sc.(Eng.).

LOCAL COMMITTEES ABROAD.

AUSTRALIA.

New South Wales.

Chairman.—V. L. MOLLOY.
Hon. Secretary.—W. J. McCALLION, M.C., c/o Electrical Engineers Branch, Dept. of Public Works, Sydney.

Queensland.

Chairman and Hon. Secretary.—J. S. JUST, c/o P.O. Box 1067N, G.P.O., Brisbane.

South Australia.

Chairman and Hon. Secretary.—F. W. H. WHEADON, Kelvin Building, North Terrace, Adelaide.

Victoria and Tasmania.

Chairman and Hon. Secretary.—H. R. HARPER, 22–32, William Street, Melbourne.

Western Australia.

Chairman.—J. R. W. GARDAM.
Hon. Secretary.—A. E. LAMBERT, B.E., 35, The Esplanade, South Perth.

CEYLON.

Chairman.—MAJOR C. H. BRAZEL, M.C.
Hon. Secretary.—G. L. KIRK, Stanley Power Station, Kolonnawa, Colombo.

INDIA.

Bombay.

Chairman.—R. G. HIGHAM.
Hon. Secretary.—A. L. GUILFORD, B.Sc.Tech., Electric House, Post Fort, Bombay.

Calcutta.

Chairman.—F. T. HOMAN.
Hon. Secretary.—D. H. P. HENDERSON, c/o Calcutta Electric Supply Corporation, Post Box 304, Calcutta.

Lahore.

Chairman.—PROF. T. H. MATTHEWMAN.
Hon. Secretary.—J. C. BROWN, c/o Associated Electrical Industries (India) Ltd., P.O. Box 146, Lahore.

Madras.

Chairman and Hon. Secretary.—E. J. B. GREENWOOD, Electricity Dept., P.W.D. Offices, Chepauk, Madras.

NEW ZEALAND.

Chairman.—F. T. M. KISSEL, B.Sc.
Hon. Secretary.—J. McDERMOTT, P.O. Box 749, Wellington, C.1.

SOUTH AFRICA.

Transvaal.

Chairman and Hon. Secretary.—W. ELSDON DEW, Box 4563, Johannesburg.

LOCAL HONORARY SECRETARIES ABROAD.

ARGENTINE: R. G. PARROTT, Avenida Pte. Roque Saenz Peña 636, Buenos Aires.
CANADA: F. A. GABY, D.Sc., Vice-President, The British American Oil Co., Ltd., 14th Floor, Royal Bank Building, Toronto, Ontario.
CAPE, NATAL, AND RHODESIA: G. H. SWINGLER, City Electrical Engineer, Corporation Electricity Dept., Cape Town.
FRANCE: P. M. J. AILLERET, 36, Avenue Kleber, Paris (16^{e}).
HOLLAND: A. E. R. COLLETTE, Heemskerckstraat, 30, The Hague.
INDIA: K. G. SILLAR, c/o Calcutta Electric Supply Corporation, Post Box 304, Calcutta.
ITALY: L. EMANUELI, Via Fabio Filzi, 21, Milan.
JAPAN: I. NAKAHARA, No. 40, Ichigaya Tanimachi, Ushigomeku, Tokio.
NEW SOUTH WALES: V. J. F. BRAIN, B.E., Chief Electrical Engineer, Department of Public Works, Bridge Street, Sydney.
NEW ZEALAND: J. McDERMOTT, P.O. Box 749, Wellington, C.1.
QUEENSLAND: J. S. JUST, c/o P.O. Box 1067N, G.P.O., Brisbane.
SOUTH AUSTRALIA: F. W. H. WHEADON, Kelvin Building, North Terrace, Adelaide.
TRANSVAAL: W. ELSDON DEW, Box 4563, Johannesburg.
UNITED STATES OF AMERICA: GANO DUNN, c/o The J. G. White Engineering Corporation, 80, Broad Street, New York, N.Y.
VICTORIA AND TASMANIA: H. R. HARPER, 22–32, William Street, Melbourne.
WESTERN AUSTRALIA: PROF. P. H. FRAENKEL, B.E., The University of Western Australia, Crawley, Perth.

STUDENTS' SECTIONS.

LONDON.

Chairman.—N. C. Rolfe.
Hon. Secretary.—P. H. Pettifor, 65, The Manor Way, Blackheath, S.E.3.

NORTH-WESTERN.

Chairman.—J. A. Henley.
Hon. Secretary.—R. M. A. Smith, Meter Engineering Dept., Metropolitan-Vickers Electrical Co., Ltd., Trafford Park, Manchester, 17.

SCOTTISH.

Chairman.—J. S. Tait.
Hon. Secretary.—G. H. Wire, 46, South Brae Drive, Jordanhill, Glasgow.

NORTH-EASTERN.

Chairman.—D. Smith.
Hon. Secretary.—J. A. Stanfield, 44, Shipley Avenue, Milvain, Newcastle-on-Tyne.

MERSEY AND NORTH WALES (LIVERPOOL).

Chairman.—A. A. Dale.
Hon. Secretary.—J. E. Houldin, 19, Alvanley Place, Birkenhead.

SOUTH MIDLAND.

Chairman.—H. S. Prosser.
Hon. Secretary.—H. J. Sheppard, 90, Prouds Lane, Bilston, Staffs.

NORTH MIDLAND.

Chairman.—W. Chambers.
Hon. Secretary.—H. M. Corner, 34, Conway Drive, Leeds, 8.

SHEFFIELD.

Chairman.—H. A. Wainwright.
Hon. Secretary.—C. C. Hall, 4, Meadow Head Avenue, Woodseats, Sheffield, 8.

BRISTOL.

Chairman.—G. L. Thorne. *Hon. Secretary.*—A. W. Britton, 56, High Street, Easton, Bristol, 5.

THE I.E.E. BENEVOLENT FUND.

The object of the I.E.E. Benevolent Fund is to help those members of The Institution and their dependants who have suffered a set-back through ill health, or who are passing through times of stress.

⁘

Applications for assistance will increase with the passage of years. During 1936, 73 cases were helped with grants amounting to £3720.

Please support the Fund

Subscriptions and Donations should be addressed to

THE HONORARY SECRETARY, THE BENEVOLENT FUND,
THE INSTITUTION OF ELECTRICAL ENGINEERS,
SAVOY PLACE, W.C.2.

⁘

LOCAL HON. TREASURERS OF THE FUND.

Irish Centre: T. J. Monaghan. *North-Eastern Centre:* N. Cresswell. *North Midland Centre:* R. M. Longman. *Sheffield Sub-Centre:* W. E. Burnand. *North-Western Centre:* T. E. Herbert. *Mersey and North Wales (Liverpool) Centre:* A. C. Livesey. *Scottish Centre:* (*Glasgow*) A. Lindsay; (*Edinburgh*) D. S. Munro. *Dundee Sub-Centre:* P. Philip. *South Midland Centre:* W. Y. Anderson. *Western Centre:* (*Bristol*) E. P. Knill; (*Cardiff*) J. W. Elliott. *Hampshire Sub-Centre:* W. P. Conly, M.Sc.

PRINTED BY UNWIN BROTHERS LIMITED, LONDON AND WOKING